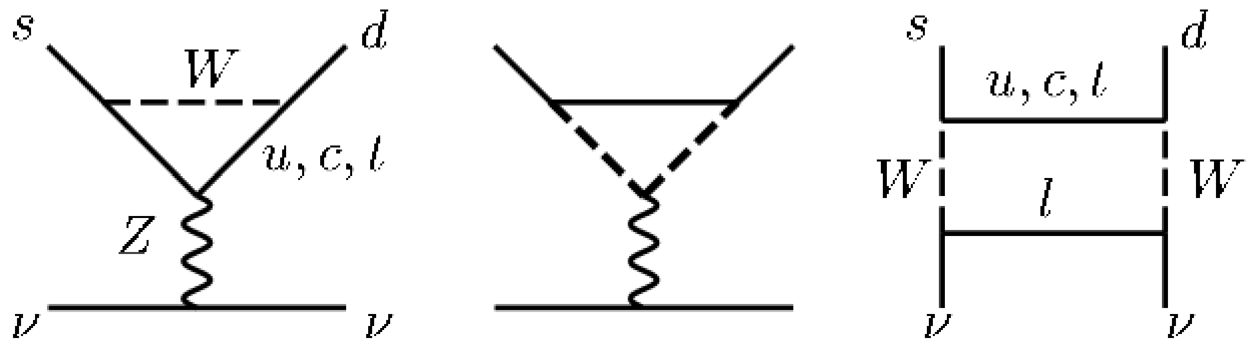
RSVP
The KOPIO Experiment
Measurement of $B(K_L \rightarrow \pi^0 \nu\bar{\nu})$

DOE Review
Brookhaven National Laboratory
April 27, 2005
David E. Jaffe

KOPIO is Unique

- **Only experiment that directly measures the area of unitary triangles (Jarlskög invariant)**
- **Excellent discovery potential for non-SM physics in $K_L \to \pi^0 \nu \bar{\nu}$**
  - **Two order of magnitude window**
  - **Many candidate theories**
  - **KOPIO constrains operators that B system can't access!**
- **Only approved experiment sensitive enough reach the SM level; uses a robust innovative technique to suppress background**

$K \to \pi\nu\bar{\nu}$ in the Standard Model



Suppressed to the 1-loop level by GIM.

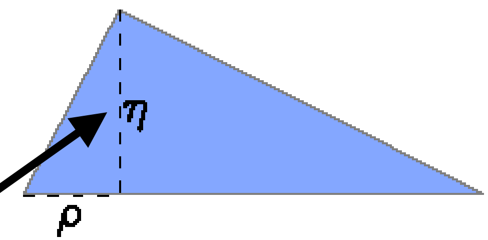
No competing long-distance contributions

$K_L \to \pi^0\nu\nu$ is t-quark dominated in the loops

Direct CP-violating to ~1%

No significant QCD correction

Hadronic m.e. from Ke3



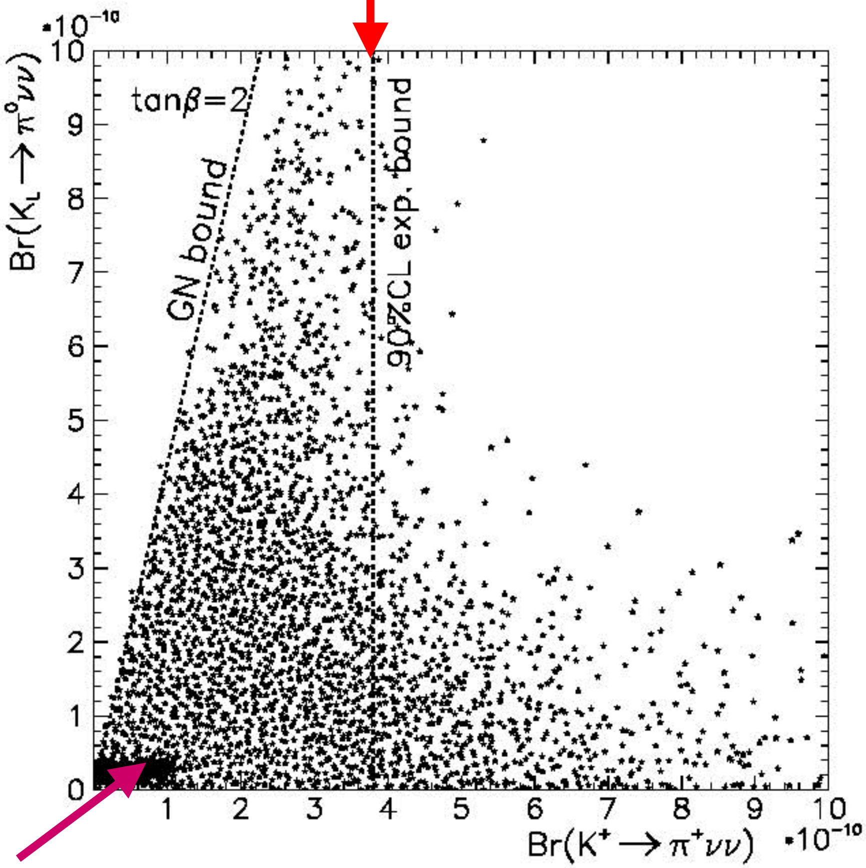
$BR = (1.558 \pm 0.025)\times 10^{-3} \bullet (1 \pm 1.3\sigma_m/m_t) \bullet (\mathrm{Im}\,\lambda_t)^2 = 3\times 10^{-11}$

< 2% intrinsic theoretical uncertainty

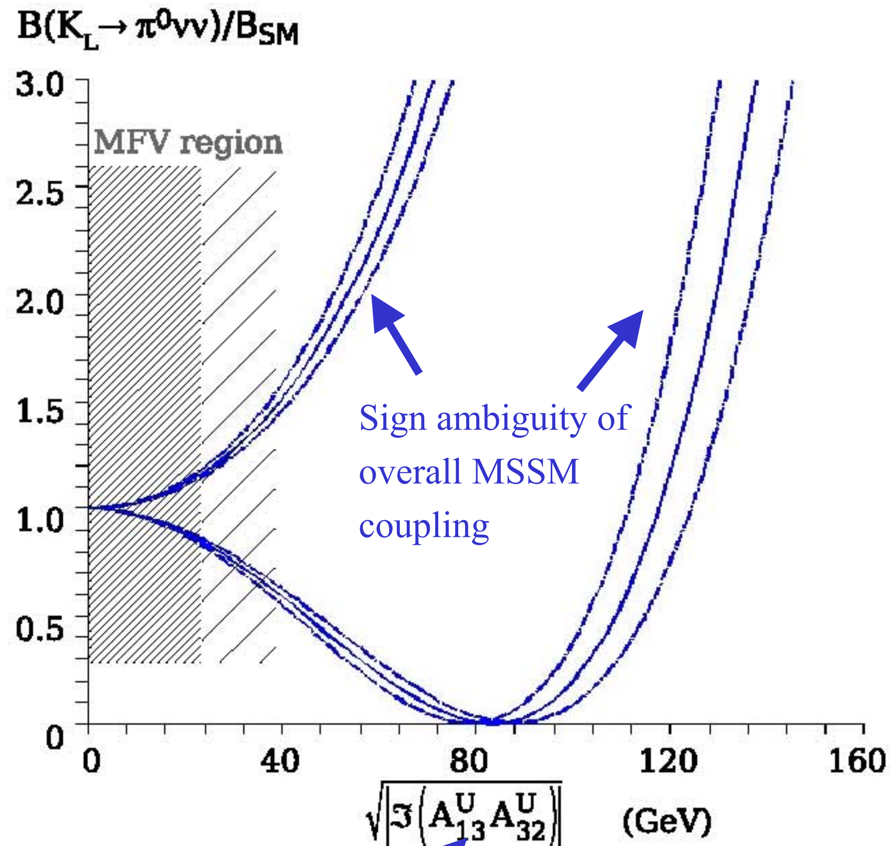
uncertainty due to that on m_t

$K \rightarrow \pi\nu\bar{\nu}$ in the MSSM

From BNL E949



SM

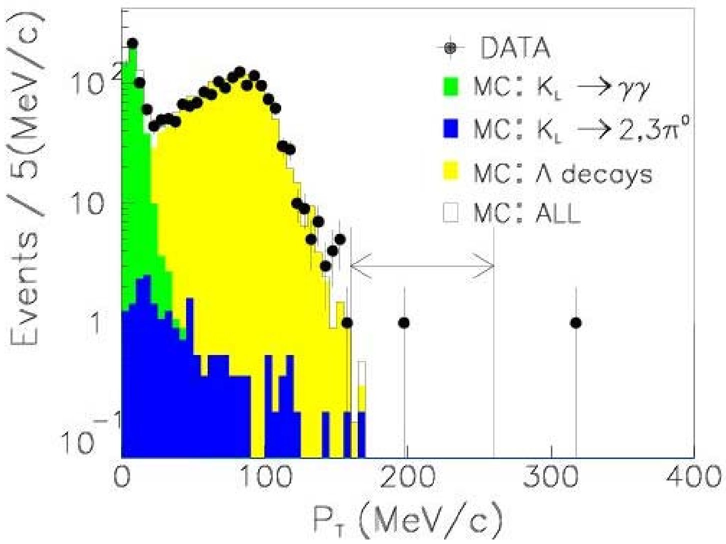


Sign ambiguity of overall MSSM coupling

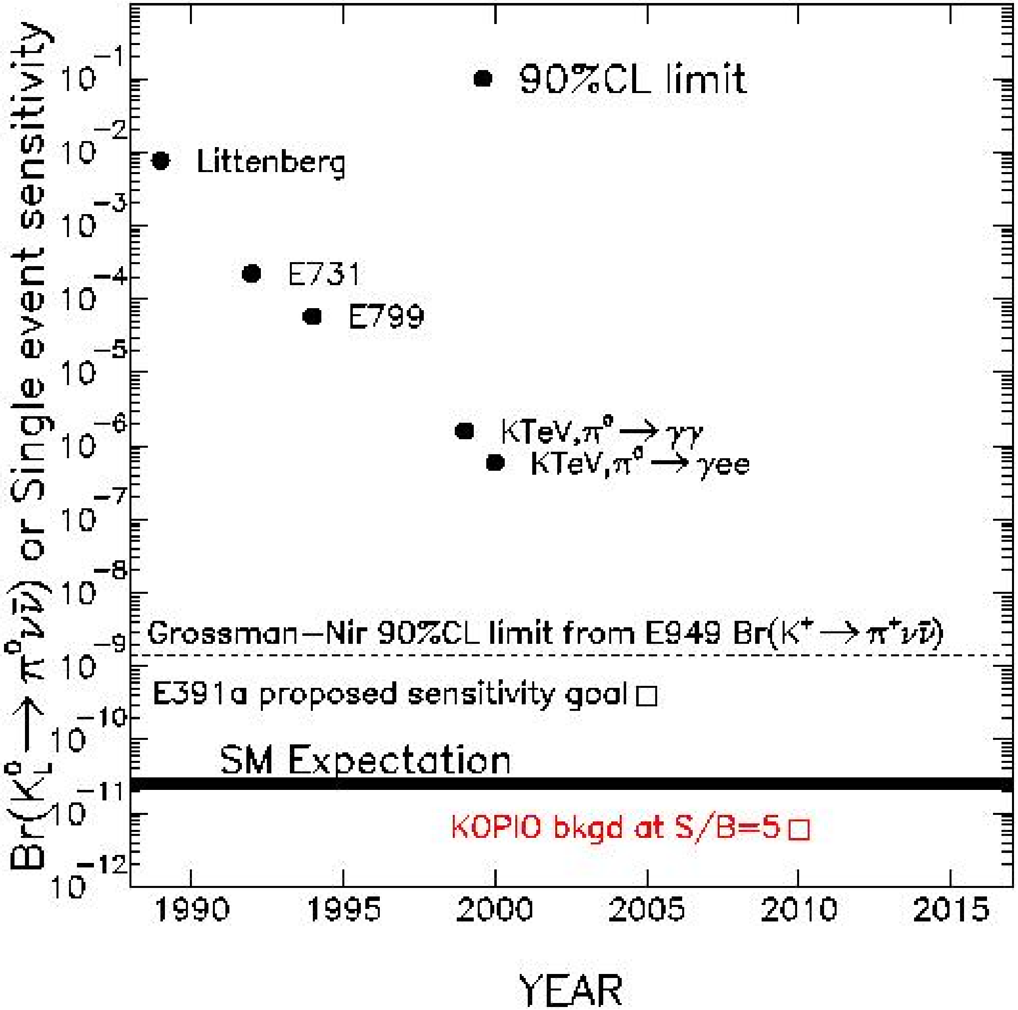
Soft breaking trilinear couplings squark & chargino masses fixed

Experimental Progress in $K_L \rightarrow \pi^0 \nu\nu$

KTeV Results using 'pencil' beam
PL **B447**(1999)240.



E391a using same technique and is the first dedicated experiment to search for $K_L \rightarrow \pi^0 \nu\nu$



KOPIO technique: work in K_L CMS

Measure everything possible

Microbunched K_L beam

Measure γ directions in PR

Measure γ energy in CAL

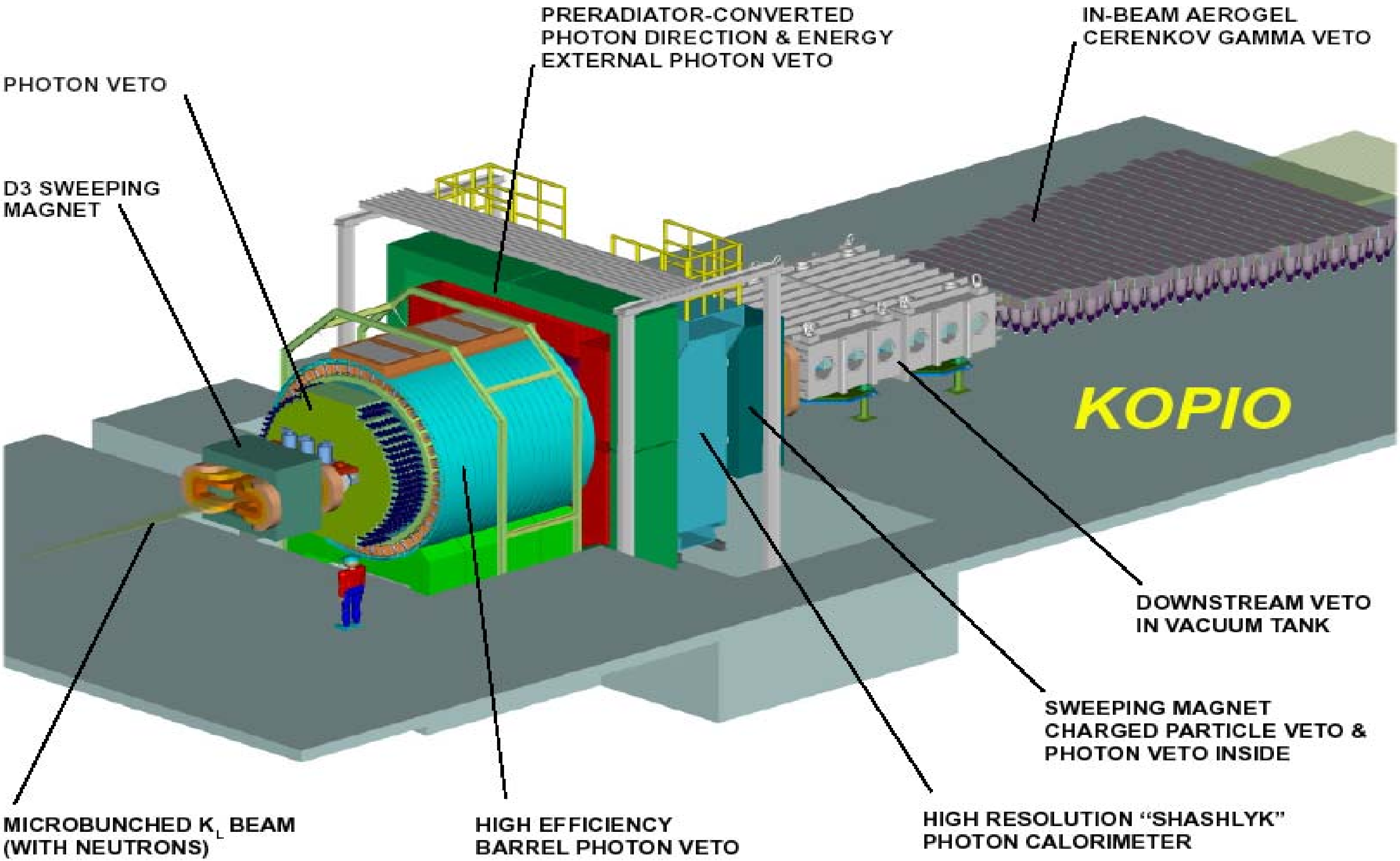
Reconstruct π^0 from $\gamma\gamma$

Measure K_L velocity from TOF

Photon Veto (PV)

Charged Particle Veto (CPV)

Kinematic veto


PRERADIATOR-CONVERTED
PHOTON DIRECTION & ENERGY
EXTERNAL PHOTON VETO
IN-BEAM AEROGEL
CERENKOV GAMMA VETO
PHOTON VETO
D3 SWEEPING
MAGNET
KOPIO
DOWNSTREAM VETO
IN VACUUM TANK
SWEEPING MAGNET
CHARGED PARTICLE VETO &
PHOTON VETO INSIDE
MICROBUNCHED K_L BEAM
(WITH NEUTRONS)
HIGH EFFICIENCY
BARREL PHOTON VETO
HIGH RESOLUTION "SHASHLYK"
PHOTON CALORIMETER

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Photon Veto (PV)

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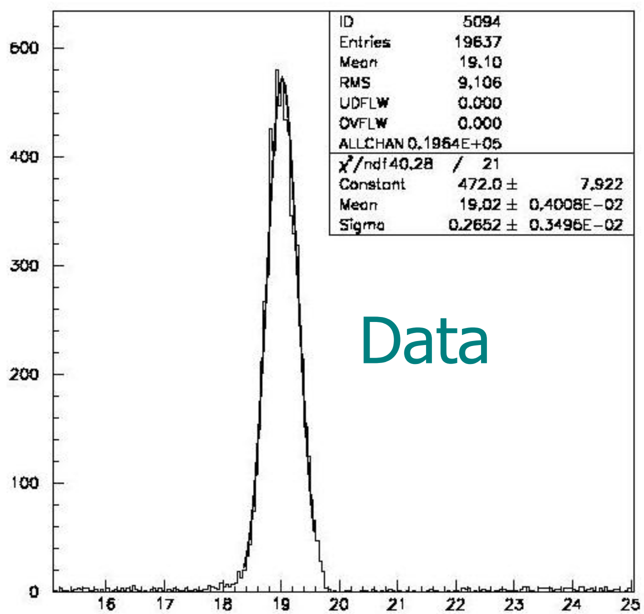
Kinematic veto

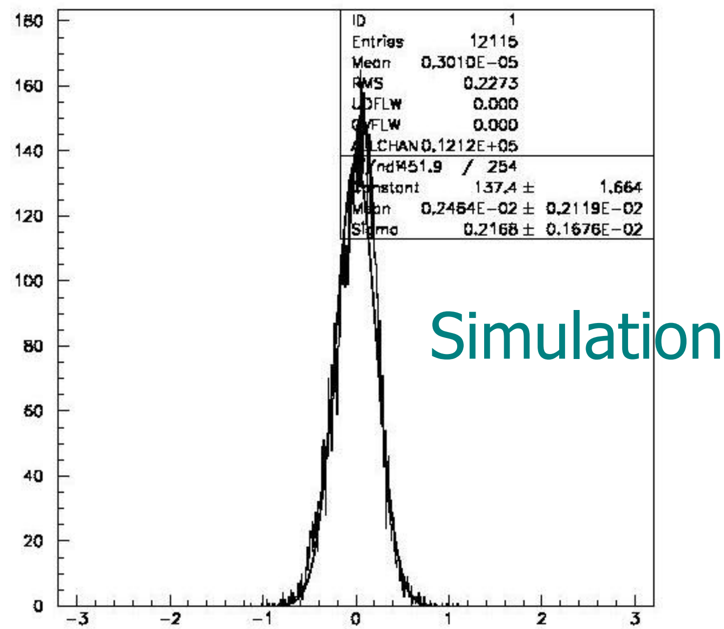
Microbunch Width

Simulations predict σ = 180ps utilizing new 25 and 100MHz cavities

Data	Simulation
93 MHz cavity at 22 kV gave σ = 240 ps.	93 MHz cavity at 22 kV gave σ = 217 ps.



Microbunch time, in ns



Microbunch time, in ns

Interbunch Extinction

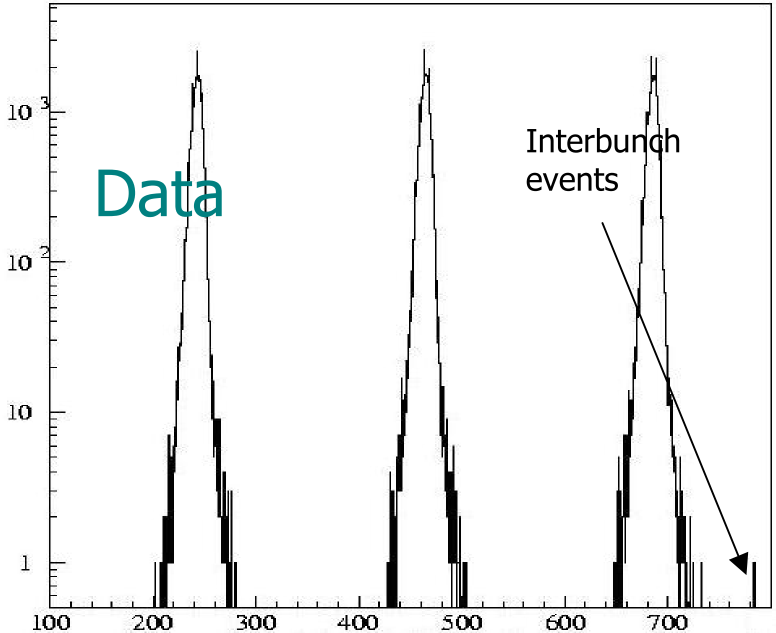
Extinction performance at high AGS intensities last remaining issue to be verified

Data

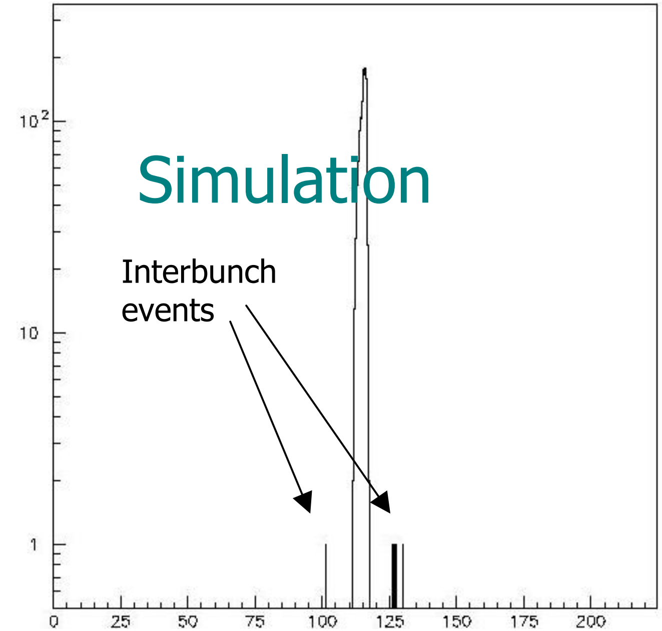
4.5 MHz cavity at 130 kV gave $\varepsilon = 8\ (+/-\ 6) \times 10^{-6}$

Simulation

4.5 MHz cavity at 130 kV gave $\varepsilon = 1.7\ (+/-\ 0.9) \times 10^{-3}$.



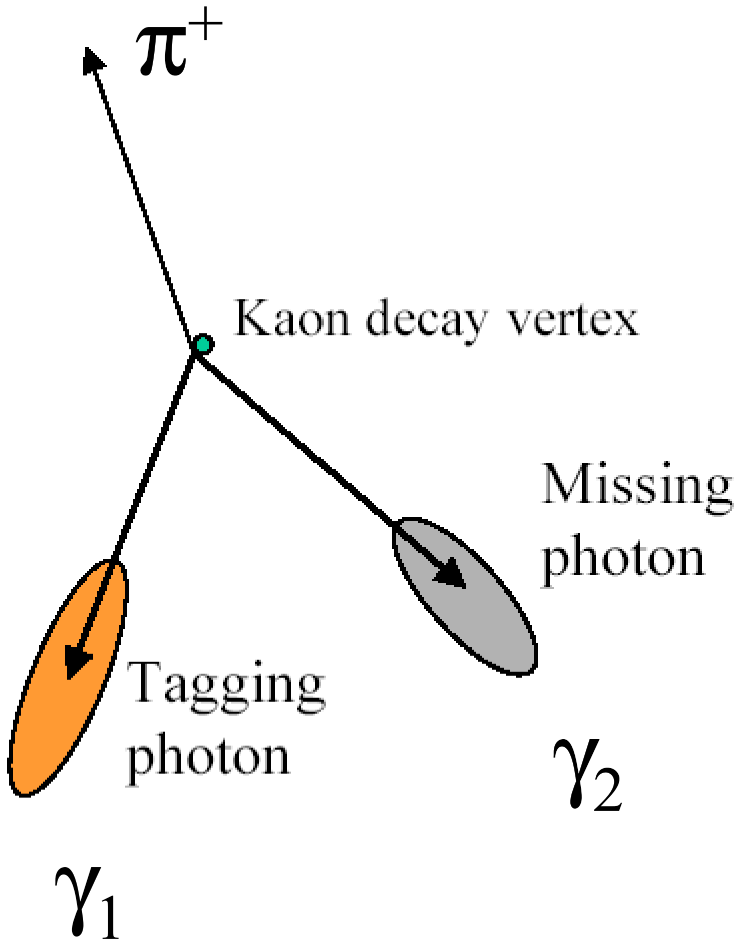
Microbunch time, in ns

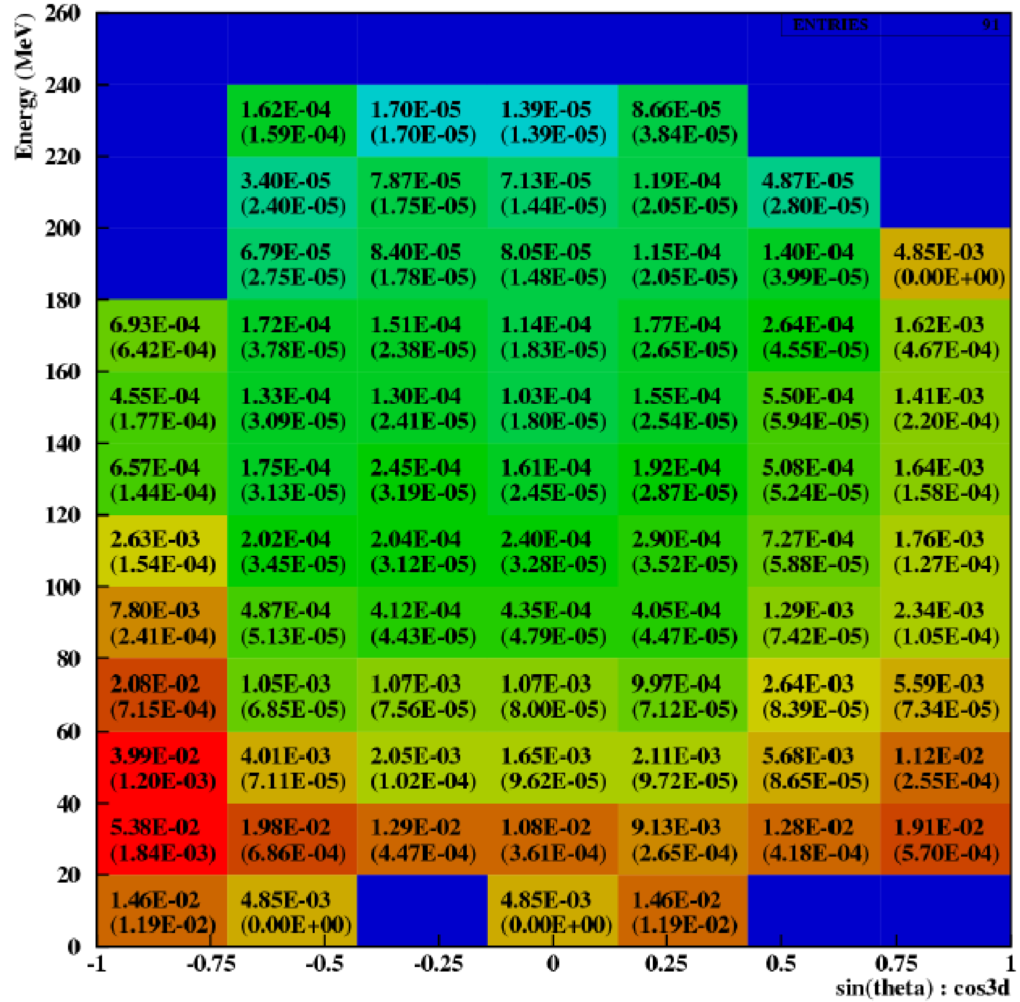


Microbunch time, in ns

E949 Single γ Ineff'y Measurement

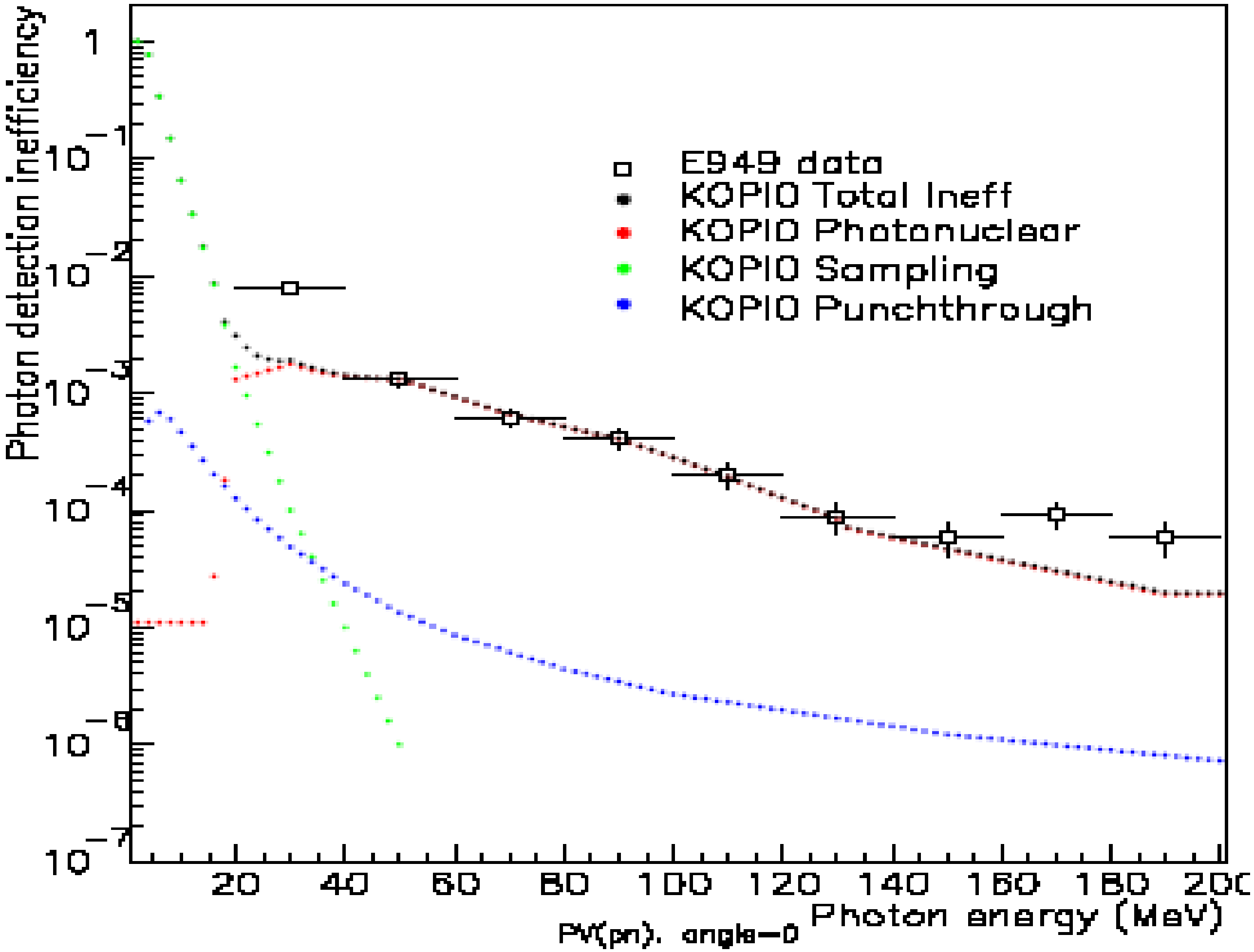
Kπ2 Decay





Photon Veto Inefficiency

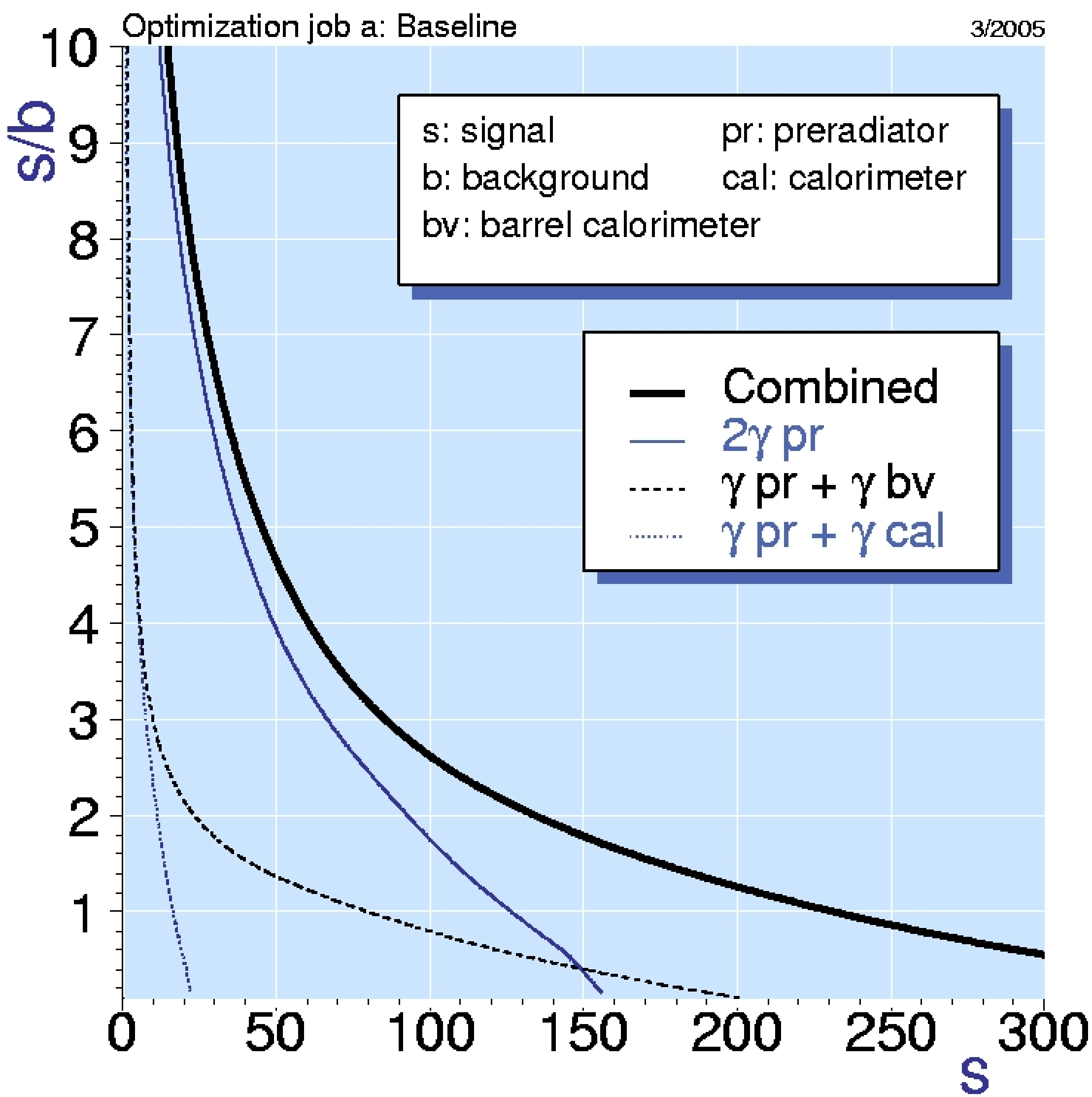
KOPIO PV Estimates and Simulations based on improved BNL E949 Measurements supplemented by FLUKA calculations



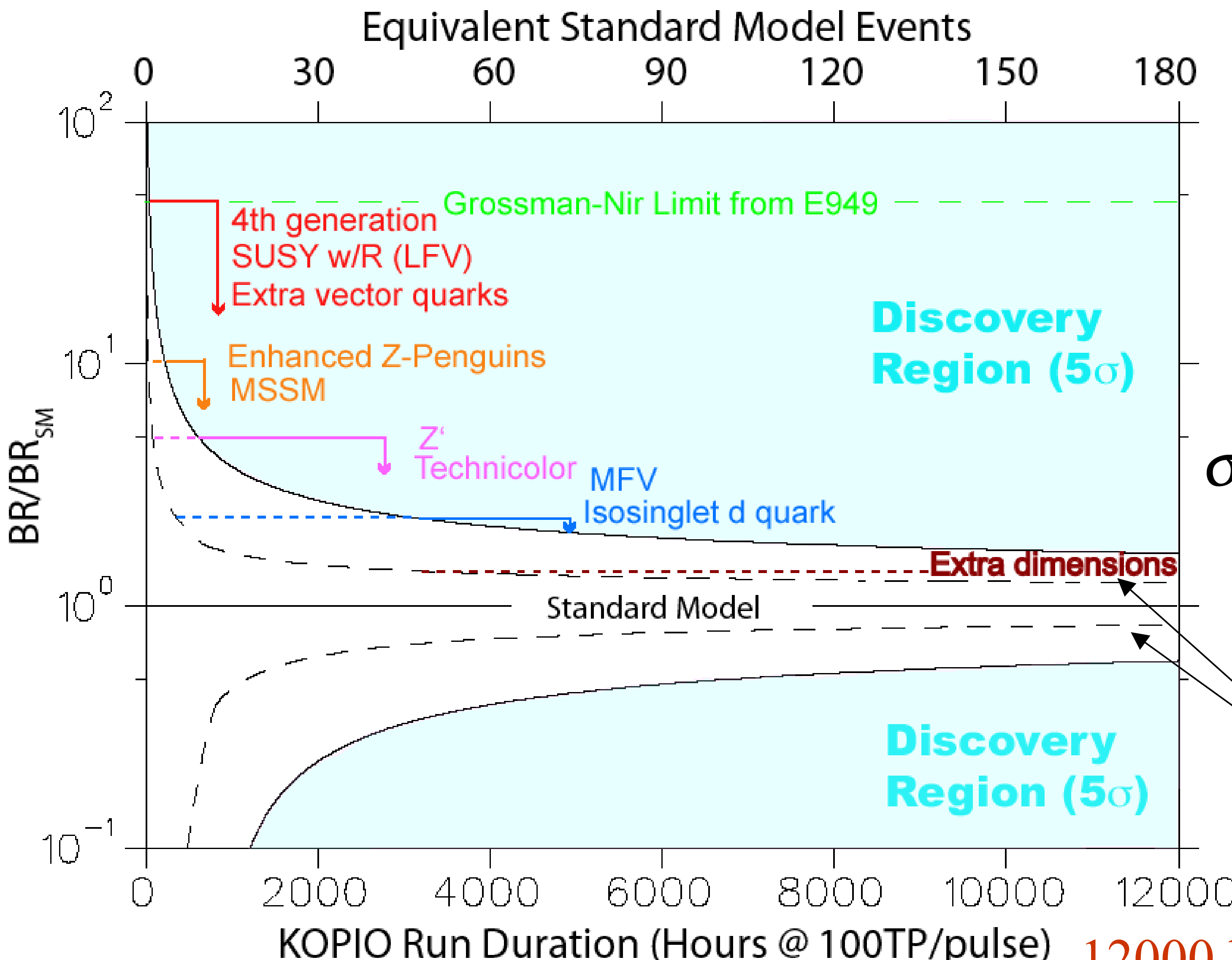
1 MeV Visible Energy Threshold

Optimized S/B vs. Signal (Events)

Expected signal-to-background (S/B) as a function of signal event yield for the KC 0^{-11}



Discovering/Constraining New Physics



Theory

$\sigma(BR)/BR \approx 2\%$

95%CL limits

12000 hours = 4years

RSVP Timeline: Overview

- 10/96 – BNL Scientific Approval for KOPIO
- 10/97 – BNL Scientific Approval for MECO
- 11/99 – Submission of RSVP to NSF as MRE candidate
- 07/00 – NSF External Cost Verification Review
- 10/00 – NSB authorizes RSVP for inclusion in President's Budget for FY02+
- 06/01 – NSF External Panel Review (science, cost, technical, management)
- 2001 – HEPAP Subpanel endorses physics goals of RSVP
- 03/02 – NSF External Panel Review (R&D progress, budgets, roadmap)
- 01/04 – DOE (Lehman) Review of RSVP impact on RHIC operations
- 02/04 – NSF proposes RSVP to Congress for FY2006 funding as MREFC
- 08/04 – DOE/NSF Interagency MoU signed regarding RSVP
- 10/04 – MECO magnet Review
- 11/04 – AGS Review
- 12/04 – Congress appropriates $15M MREFC & construction start for FY05
- 01/05 – Simulations and backgrounds Review
- 03/05 – HEPAP Subpanel on RSVP science value convened
- 04/05 – NSF Baseline Review ← **We are here**
- 08/05 – NSB decision on RSVP startup

KOPIO Project/Collaboration
(6 countries, 19 institutions, 90 physicists)

Arizona State University J.R. Comfort, J. Figgins

University of British Columbia, Canada D. Bryman, M. Hasinoff, J. Ives

Brookhaven National Laboratory D. Beavis, I.-H. Chiang, A. Etkin, J.W. Glenn, A. Hanson, D. Jaffe, S. Kettell, D. Lazarus, K. Li, L. Littenberg, G. Redlinger, C. Scarlett, M. Sivertz, R. Strand

University of Cincinnati K. Kinoshita

IHEP, Protvino, Russia G. Britvich, V. Burtovoy, S. Chernichenko, L. Landsberg, A. Lednev, V. Obraztsov, R. Rogalev, V. Semenov, M. Shapkin, I. Shein, A. Soldatov, N. Tyurin, V. Vassil'chenko, D. Vavilov, A. Yanovich

INR, Moscow, Russia M. Khabibullin, A. Khotjanzev, Yu. Kudenko, V. Matushkko, O. Mineev, N. Yeshov

KEK, Japan M. Kobayashi

Kyoto University of Education, Japan R. Takashima

Kyoto University, Japan H. Morii, Y. Nakajima, T. Nomura, N. Sasao, T. Sumida, N. Taniguchi, H. Yokoyama

University of Montreal, Canada J.-P. Martin

University of New Mexico B. Bassalleck, N. Bruner, D.E. Fields, J. Lowe, T.L. Thomas

INFN, University of Perugia, Italy E. Imbergamo, A. Nappi, M. Valdata, M. Viti

Stony Brook University N. Cartiglia, I. Christidi, M. Marx, P. Rumerio, R.D. Schamberger

TRIUMF, Vancouver, Canada P. Amaudruz, M. Barnes, J. Doornbos, P. Gumplinger, R. Henderson, N. Khan, J. Mildenberger, A. Miller, A. Mitra, T. Numao, R. Poutissou, F. Retiere, A. Sher, G. Wait

Tsinghua University, Beijing, China S. Chen

University of Virginia E. Frlez, D. Pocanic

Virginia Polytechnic Institute and State University M. Blecher, N. Graham, A. Hatzikoutelis

Yale University G. Atoyan, S.K. Dhawan, V. Issakov, A. Poblaguev, M.E. Zeller

Students

University of Zurich, Switzerland P. Robmann, P. Truöl, A. van der Schaaf, S. Scheu

KOPIO is an international collaboration that benefits from guidance and coordination provided by BNL scientists

KOPIO Project Organization

WBS	System	Sub-System Manager	Institutions
1.2	KOPIO	M. Marx	
1.2.1	Vacuum System	Ralph Brown	BNL, Stony Brook
1.2.2	Preradiator	Toshio Numao	TRIUMF, Montreal, UBC
1.2.3	Calorimeter	Vladimir Issakov	Yale, IHEP
1.2.4	Charged Particle Veto	Andries van der Schaaf	Zurich,BNL,Kyoto,Yale
1.2.5	Photon Veto	Oleg Mineev	INR,IHEP,VaTech
1.2.6	Catcher	Noburo Sasao	KEK, Kyoto, Kyoto UE
1.2.7	Trigger	Nello Nappi	Perugia (informal)
1.2.8	DAQ	George Redlinger	BNL
1.2.9	Offline Computing	Renee Poutissou	TRIUMF, BNL, All
1.2.10	Systems Integration	Dana Beavis	BNL
1.2.11	Project Services	Jesse Becker	BNL, SBU
	FEE	Dean Schamberger	SBU
	AGS Mods	Michael Sivertz	BNL
	Beams	Dana Beavis	BNL
	Simulations	David Jaffe	BNL

DOE-supported physicists in Physics Department

KOPIO activities by BNL scientists*

SubSystem Managers: Simulation, Neutral beam, AGS, DAQ, Systems integration, Vacuum

Scrub team leaders for NSF review: CAL/PV, CPV, Trigger/DAQ/Offline/FEE, Beam catcher, Parameters

Chapter authors for CDR: Intro., Theory, DAQ, FEE, Beam, AGS, Operations, Signal & Backgrounds, Other physics

Design&construction: Beam, CPV, PV, Trigger, DAQ, Integration

Outreach/Mentoring: 7 students/2004, $\geq$5 students/2005

Analysis: Testbeam data, simulated data

Co-Spokesman: L.Littenberg

*DOE-supported physicists in Physics Department

Summary

Excellent discovery potential for non-SM physics

– Unique connection with underlying parameters

– Extremely rapid progress in first part of run

At SM value of $B(K_L \rightarrow \pi^0 \nu\nu)$

– Expect ~300 events, BR precision: ±10%; $\mathrm{Im}\lambda_t$:±5%

– Rule out non-SM effects outside $(1 \pm 0.17) \times BR_{SM}$

BNL scientists have an essential role in KOPIO concept, guidance, design, construction and analysis

Extras

BNL scientists and KOPIO

BNL physics dept scientists currently participating on KOPIO

D.Beavis: Integration SSM,Vacuum,CDR

J.Frank : CPV STL, CPV construction

D.Jaffe : Sim. SSM, Parameters STL, CDR, 2 students/2004,1 student/2005

S.Kettell: Trig/DAQ/Offline/FEE STL, Trigger

L.Littenberg: Spokesman,CDR,1student/2004,1student/2005

G.Redlinger: DAQ SSM,CDR,PV ineff'y,1student/2004

C.Scarlett:CDR,1student/2004,2students/2005

M.Sivertz:AGS SSM,CAL/PV STL, CDR, CPVconstruction, microbunch testbeam,2students/2004,1student/2005

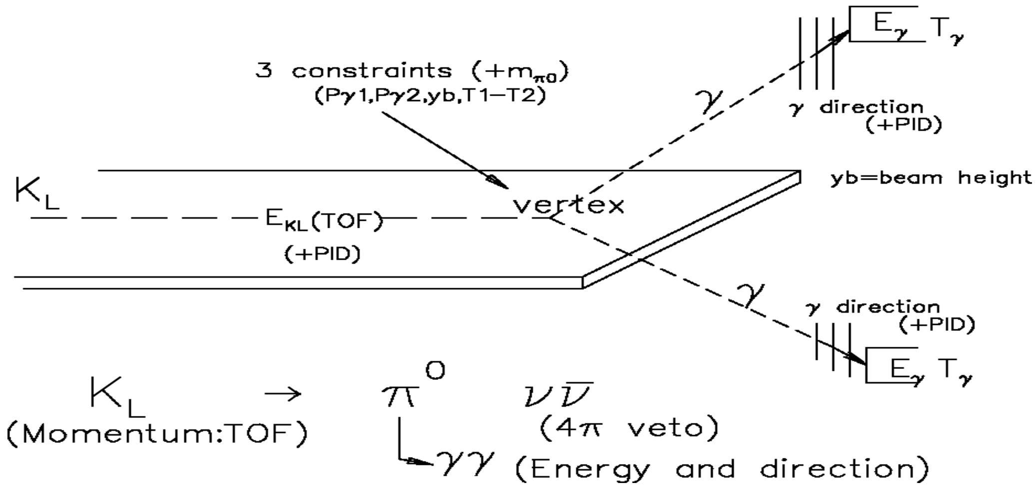
STL=Scrub Team Leader for Apr05 NSF review

CDR=author of chapter(s) in KOPIO Conceptual Design Report for Apr05 NSF review

The Challenge of KOPIO

- $B(K_L \to \pi^0 \nu\bar{\nu}) \sim 3\times10^{-11}$, need huge flux of K's
  - rates inevitably rather high
- Kinematic signature weak (2 particles undetectable)
- Backgrounds with π^0 up to 10^{10} times larger
- Veto inefficiency on extra particles must be $\leq 10^{-4}$
- Huge flux of neutrons in beam
  - can make π^0 off residual gas – require high vacuum
  - halo must be very small
  - hermeticity requires photon veto in this beam
- Need convincing measurement of background

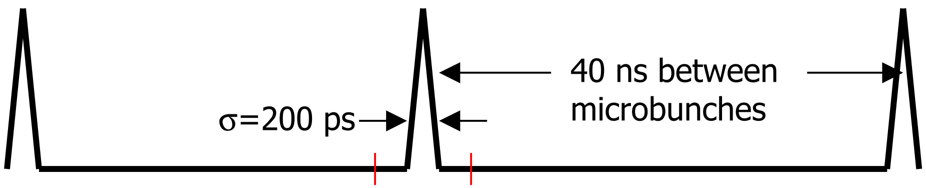
KOPIO Technique



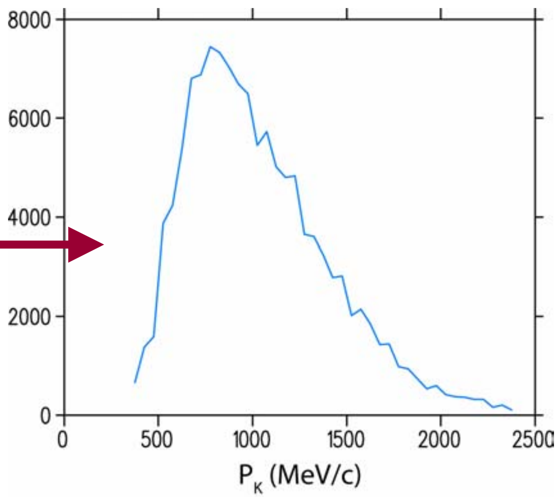
- High intensity micro-bunched beam from the AGS
- Measure everything! (energy, position, angle, time)
- Eliminate extra charged particles or *photons*
  - KOPIO: π^0 inefficiency < 10^{-8}
- Suppress backgrounds
  - Predict backgrounds *from data*:dual cuts
  - Use “blind” analysis techniques
  - Test predictions “outside the box”
- Weight candidate events with S/N likelihood function

Need AGS to provide

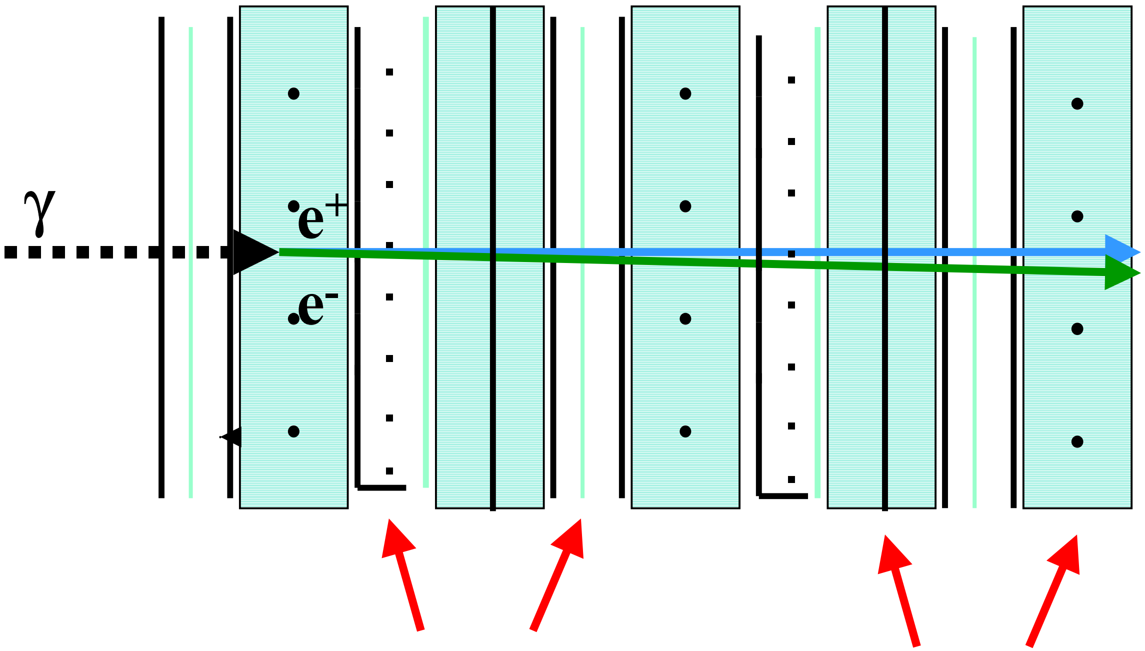
- **Proton Beam**
  - **100TP/spill (upgraded from present 70TP)**
  - **~5s spill, 2.3s interspill**
  - **Microbunching**
    - **Extract debunched beam resonantly between empty buckets**
    - **25MHz frequency**
    - **200ps bunch width**
    - **10^{-3} interbunch extinction**

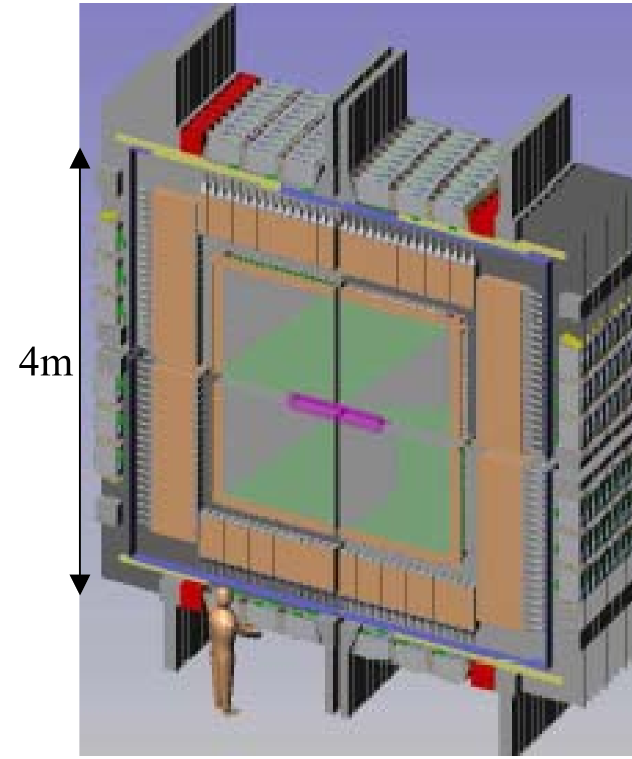


- **Kaon Beam**
  - **42.5^{o} take-off angle**
  - **Soft momentum spectrum**
    - **0.5-1.5 GeV/c**
  - **3 $\times 10^{8}$ K_L/spill**
    - **8% decay**
  - **10 GHz neutrons**

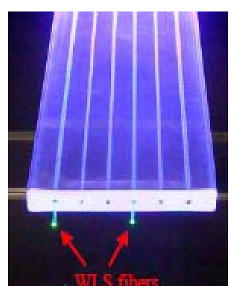


Preradiator – convert & measure γ properties





Cathode strip drift chambers

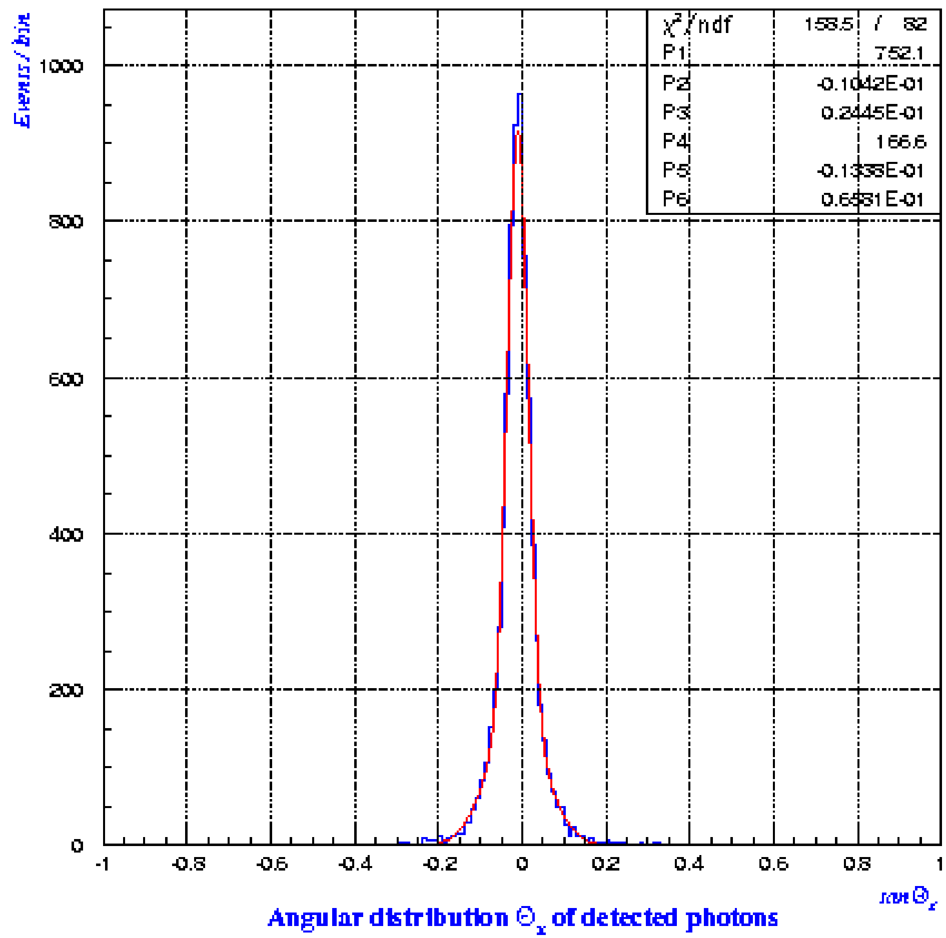


Extruded Scintillator & WLS fibers

64 Layers (4% X_0/layer, 2.7 X_0)
256 Chambers
288 Scintillator Plates (1200 m^{2})
150,000 Channels Readout

KOPIO Prototype Measurements – BNL LEGS Tagged Photon Beams

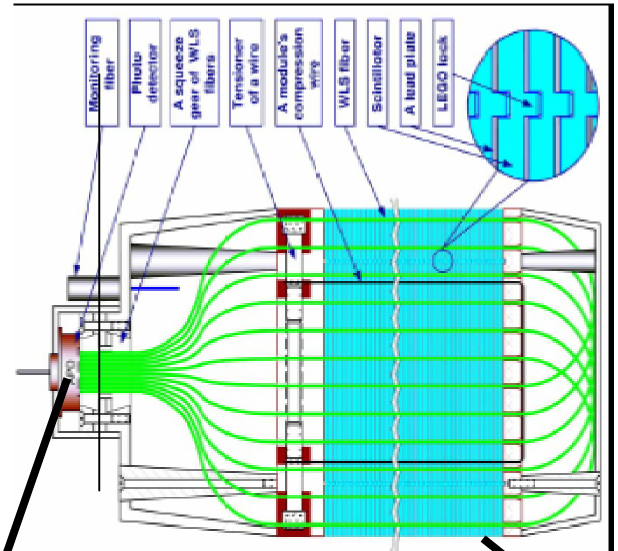
Preradiator Angular resolution: 25 mr at 250 MeV/c

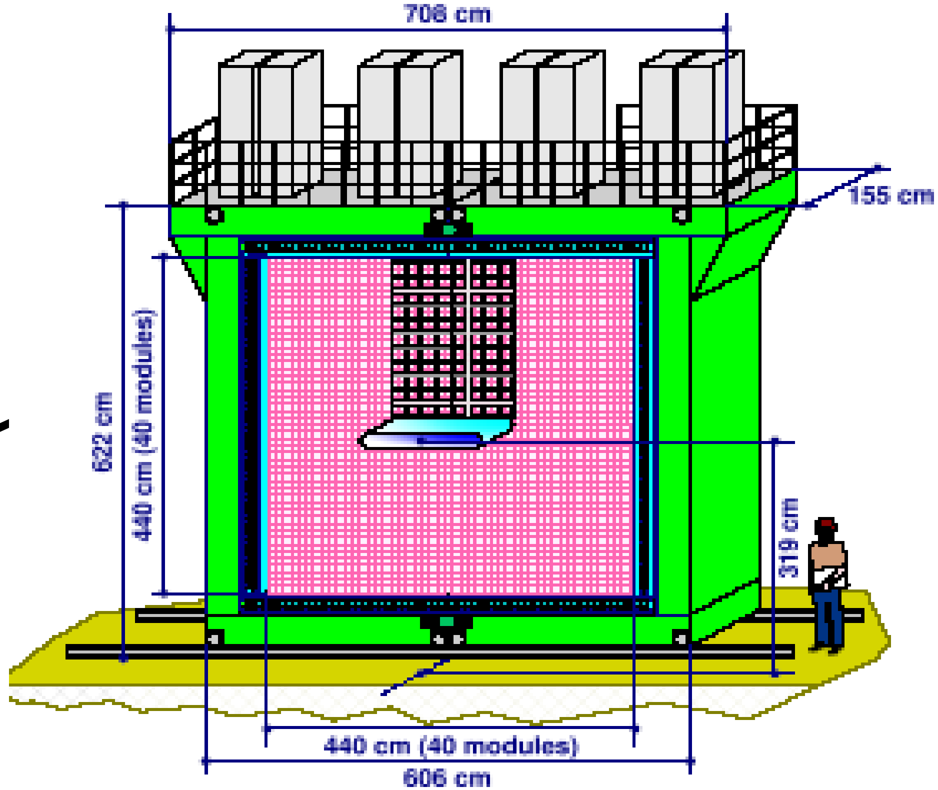


Simulations agree with measurements.

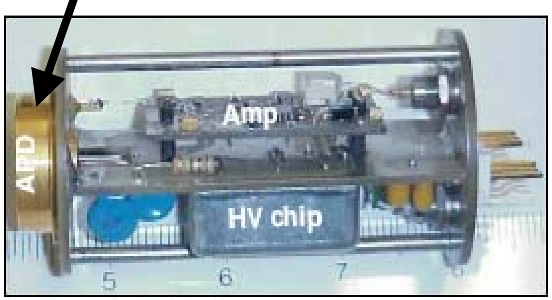
Shashlyk Photon Calorimeter

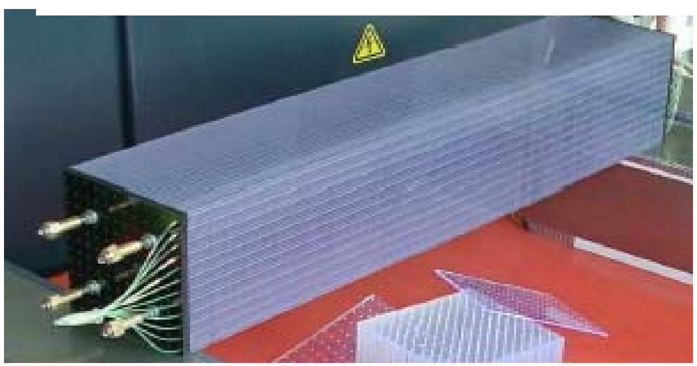
Shashlyk modules prototyped and tested in beams. Required specs have all been met



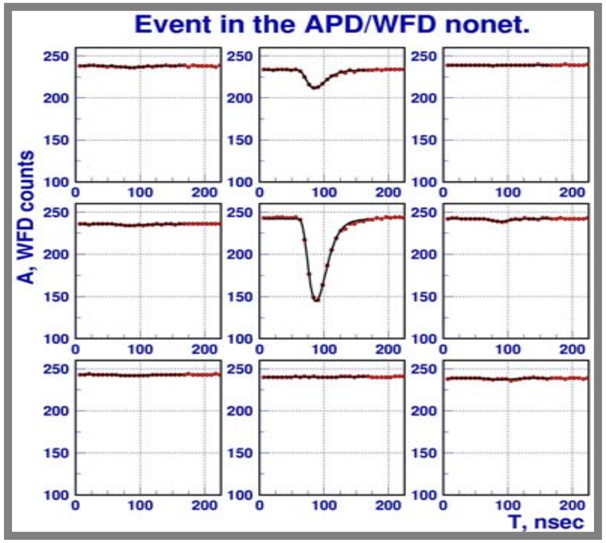


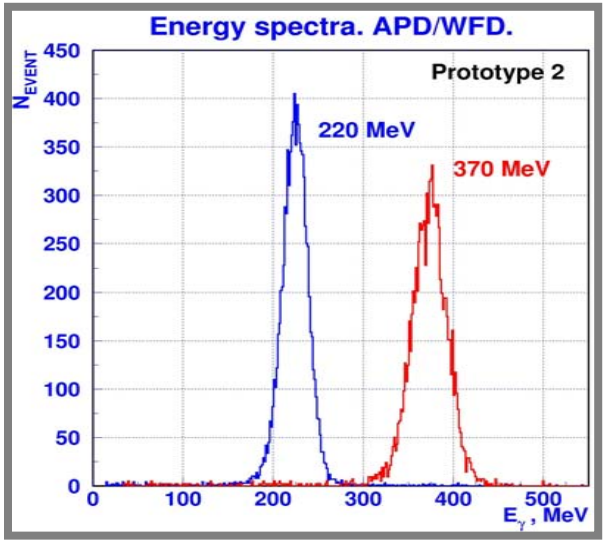
APD

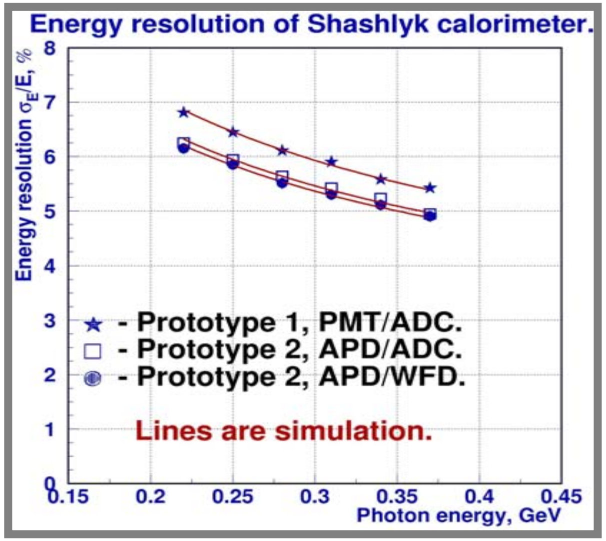


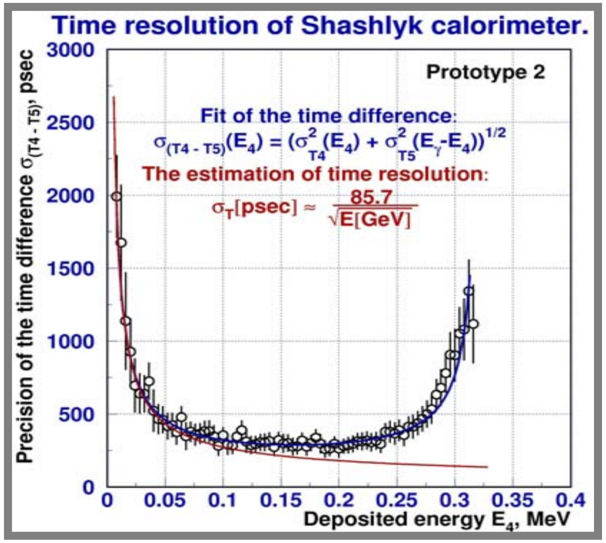


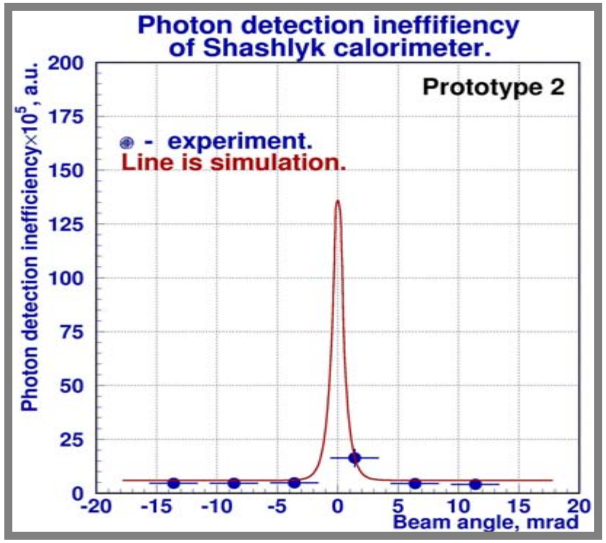
Beam test of Calorimeter modules











Simulation:
Combined PR +CAL
Energy Resolution

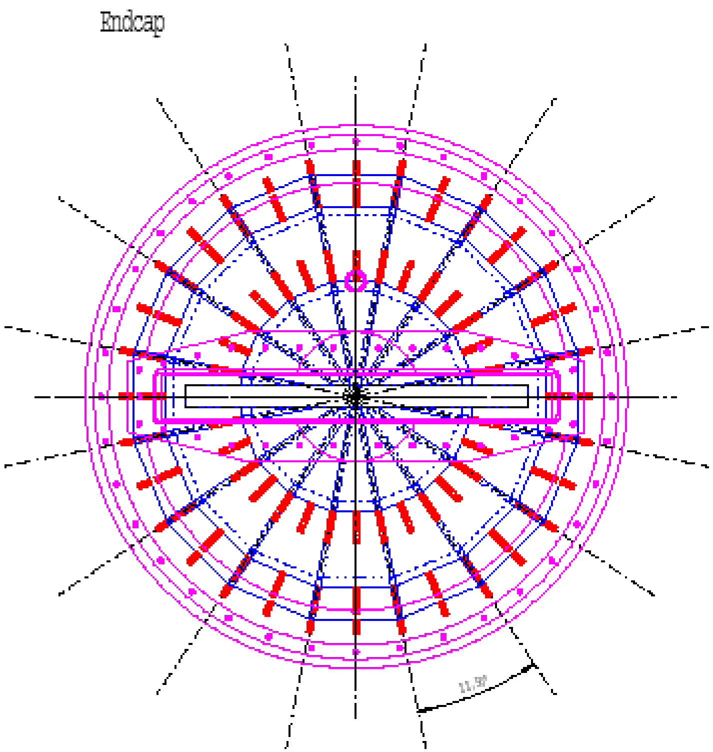
$$\sigma = \frac{2.7\%}{\sqrt{E(GeV)}}$$

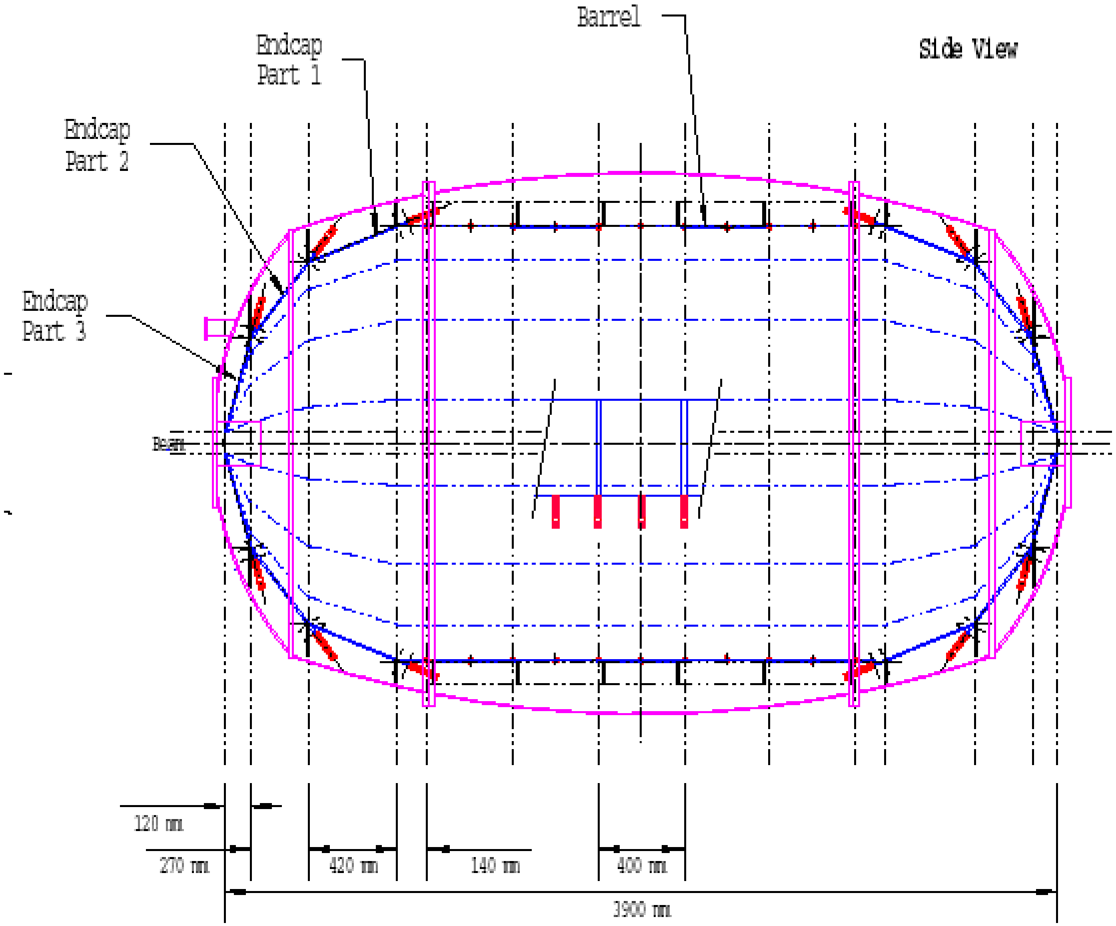
Charged Particle Veto in vacuum

CPV Barrel Detector

Total Area of Scintillator: ~34m²

Total Number of Elements: 180
Total Number of Photomultipliers: 364

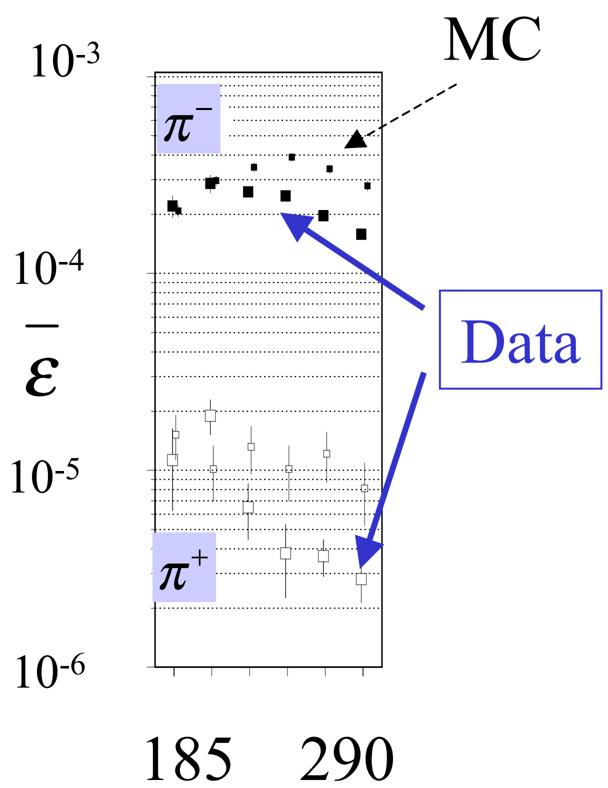


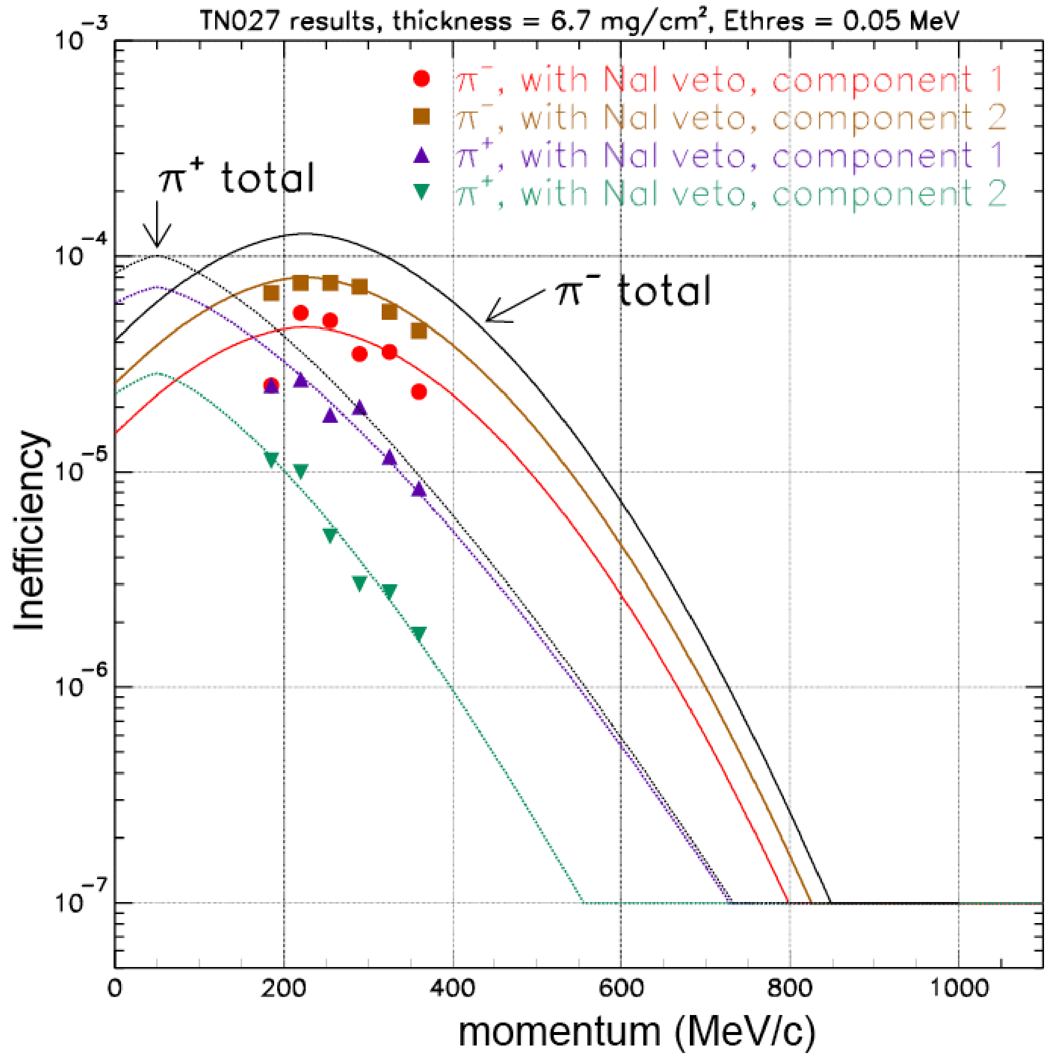


Charged Particle Veto Performance

Plastic Scintillator –

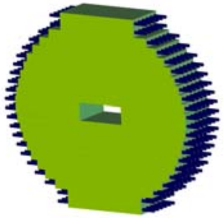
backed up by γ vetoes!





Every detector is a photon veto!

US Wall



Barrel veto

Fine-sampling lead/scintillator-based shower counters of shashlyk & bar geometry. All thick enough so punch-through not an issue. All with sufficient efficiency

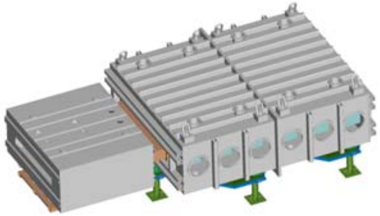
Preradiator

Prerad outer veto

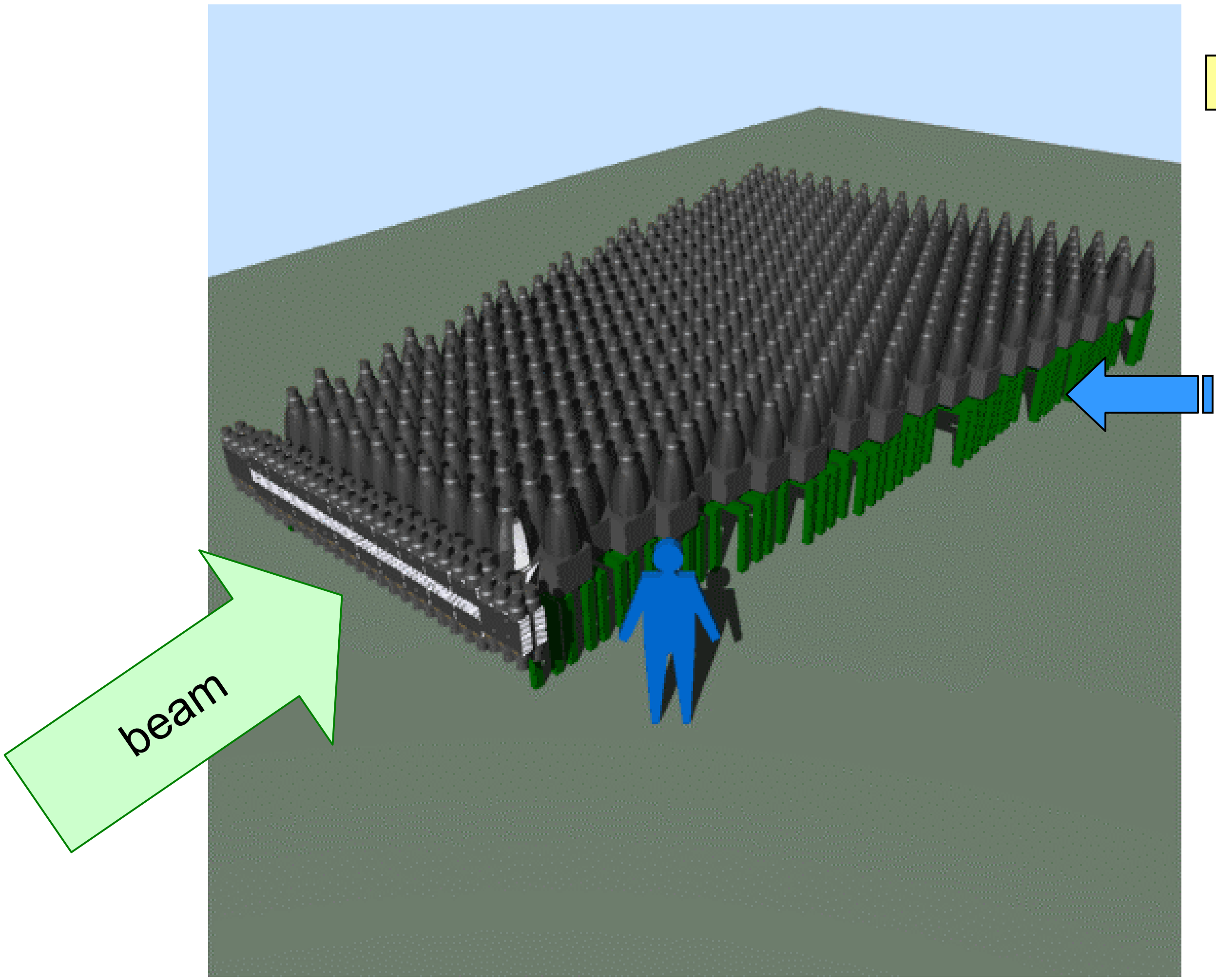
Calorimeter

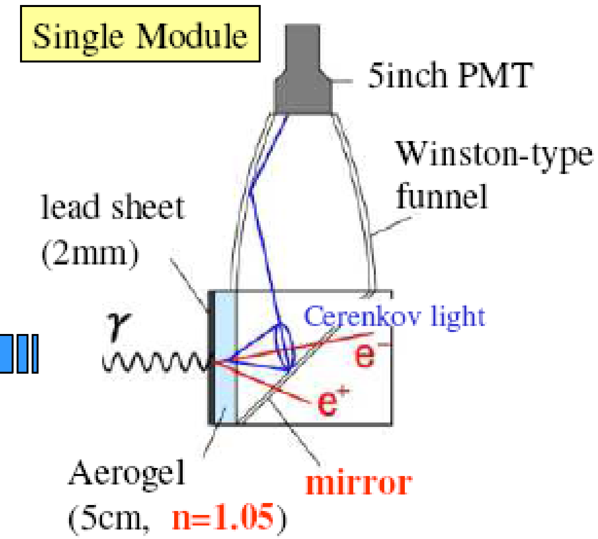
γ vetoes in D4 sweeping magnet

γ vetoes in DS vacuum pipe



Catcher: Hadron Blind Beam γ Veto



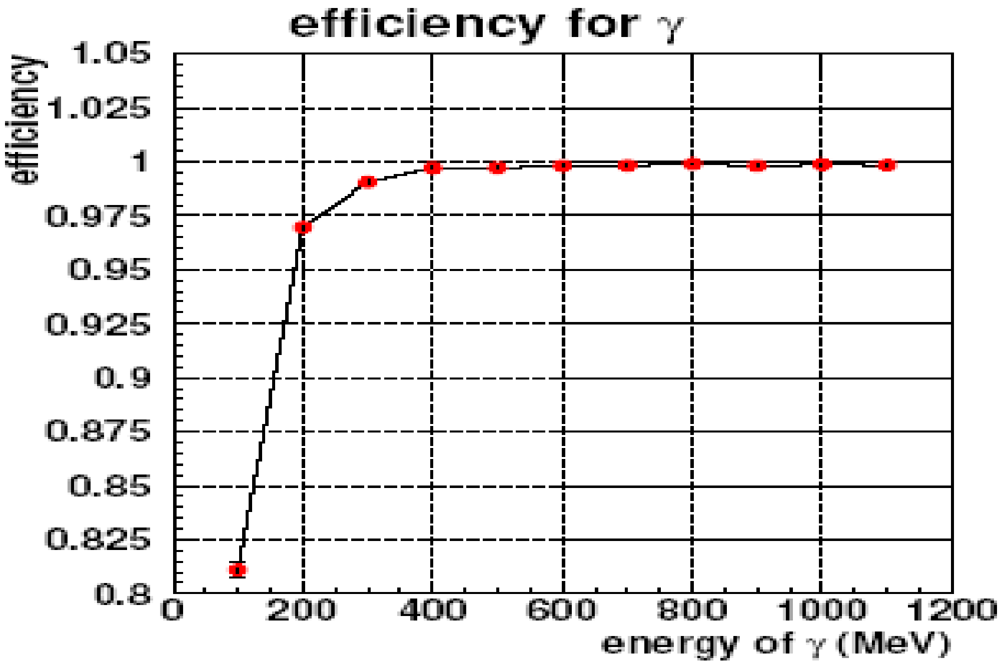


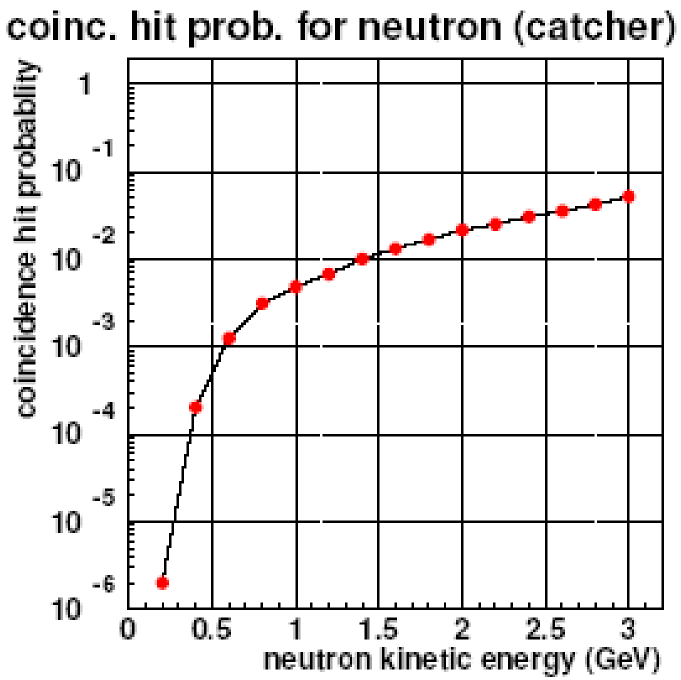
Aerogel Counter

420 modules of
Pb-Aerogel counter

Catcher R&D results

Modules prototyped and tested in beams.





K_L modes simulated for bkgnd studies

Name	Final state	Branching fraction	$\mathcal{B}/\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$
Kpnn	$\pi^0\nu\bar{\nu}$	0.3000×10^{-10}	1.000
Kp2	$\pi^0\pi^0$	0.9320×10^{-3}	0.31×10^{8}
Kcp2	$\pi^+\pi^-$	0.2090×10^{-2}	0.70×10^{8}
Kgg	$\gamma\gamma$	0.5900×10^{-3}	0.20×10^{8}
Kp3	$\pi^0\pi^0\pi^0$	0.2105	0.70×10^{10}
Kcp3	$\pi^+\pi^-\pi^0$	0.1259	0.42×10^{10}
Ke3	$\pi^\pm e^\mp\nu$	0.3881	0.13×10^{11}
Km3	$\pi^\pm\mu^\mp\nu$	0.2719	0.91×10^{10}
Ke3g	$\pi^\pm e^\mp\nu\gamma$	0.3530×10^{-2}	0.12×10^{9}
Km3g	$\pi^\pm\mu^\mp\nu\gamma$	0.5700×10^{-3}	0.19×10^{8}
Kpgg	$\pi^0\gamma\gamma$	0.1410×10^{-5}	0.47×10^{5}
Ke4	$\pi^0\pi^\pm e^\mp\nu$	0.5180×10^{-4}	0.17×10^{7}
Km4	$\pi^0\pi^\pm\mu^\mp\nu$	0.1400×10^{-4}	0.47×10^{6}
Ke2g	$e^+e^-\gamma$	0.1000×10^{-4}	0.33×10^{6}
Km2g	$\mu^+\mu^-\gamma$	0.3590×10^{-6}	0.12×10^{5}

Largest back-grounds

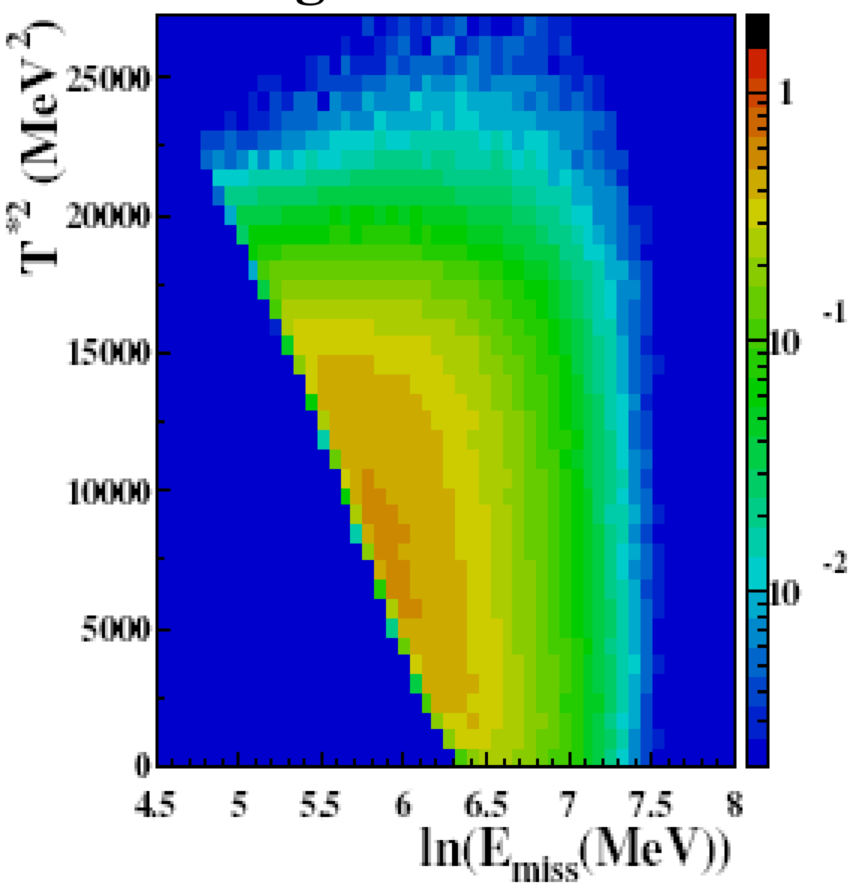
Other Backgrounds

- K^+ contamination of beam: <0.001 of signal rate
- $K_L \rightarrow K^+ e^- \nu$, $K^- e^+ \nu$: ~ 0.001 of signal rate
- $nN \rightarrow \pi^0 N$: negligible production from residual gas in decay volume if pressure<10^{-6} Torr. Requirements on reconstructed $Z_V(K_L)$ suppress rate from US wall to <0.01 of signal rate
- $\bar{n}$: far smaller than neutron background
- Hyperons: <10^{-5} of signal rate
- Fake photons < 0.05 of signal rate assuming ~$10^{-3} \times 10^{-3}$ suppression from (vetoing) $\times$ (γ/n discrimination)
- Two K_L giving single candidate: negligible due to vetoes
- $(K_L \rightarrow \pi^{\pm} X) \times (\pi^{\pm} \rightarrow \pi^0 e^{\pm} \nu)$: ~0.01 of signal rate
- $K_S \rightarrow \pi^0 \pi^0$: ~$4 \times 10^{-4}$ of $K_L \rightarrow \pi^0 \pi^0$ background rate

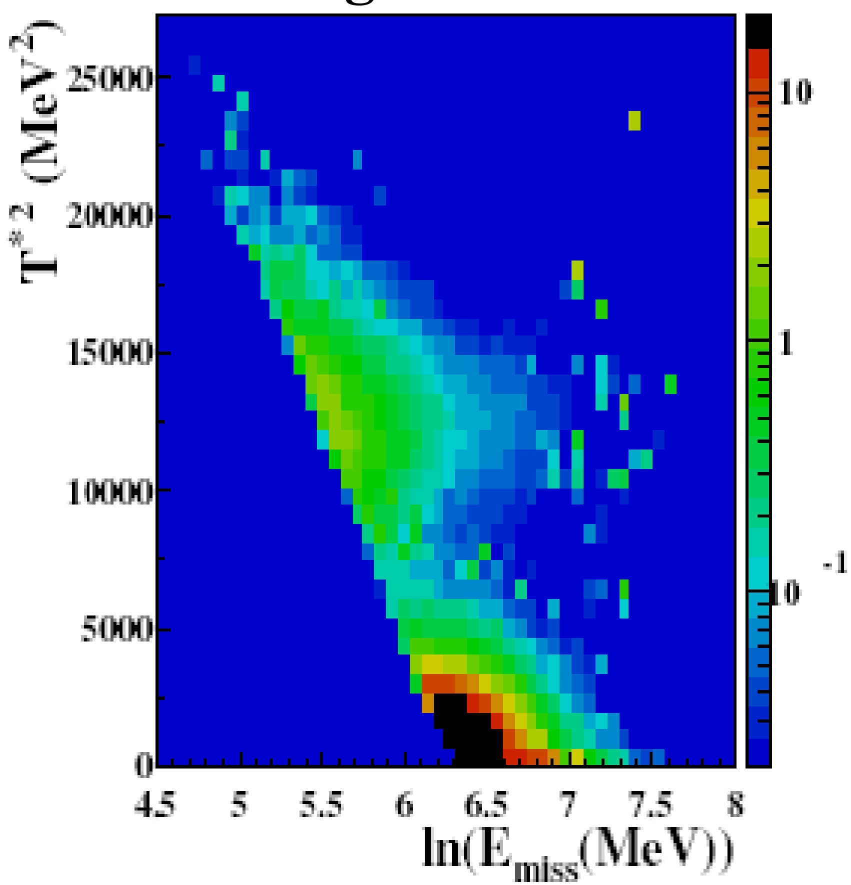
Kinematic Separation of Signal &Backgrounds

Pion kinetic energy squared (T^{*2}) vs Ln(Missing Energy)

Signal



Backgrounds



Roles of $K \to \pi\nu\bar{\nu}$ Measurements in Flavor Physics

New flavor physics in the s-d sector may be very different from that in the b sector:

* *If B-physics is consistent with the SM:*

New physics could be revealed $K \to \pi\nu\bar{\nu}$.

* *If deviations from the SM are indicated :*

$K \to \pi\nu\bar{\nu}$ would add crucial additional information; the complexity of the flavor sector beyond the SM is foreseen in many models.

Results from $K \to \pi\nu\bar{\nu}$ will be needed to interpret non-SM physics discoveries at BABAR, BELLE, CDF/D0, and the LHC.

Experiments Seeking $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

$$\text{SM: } B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.6) x 10^{-11}$$

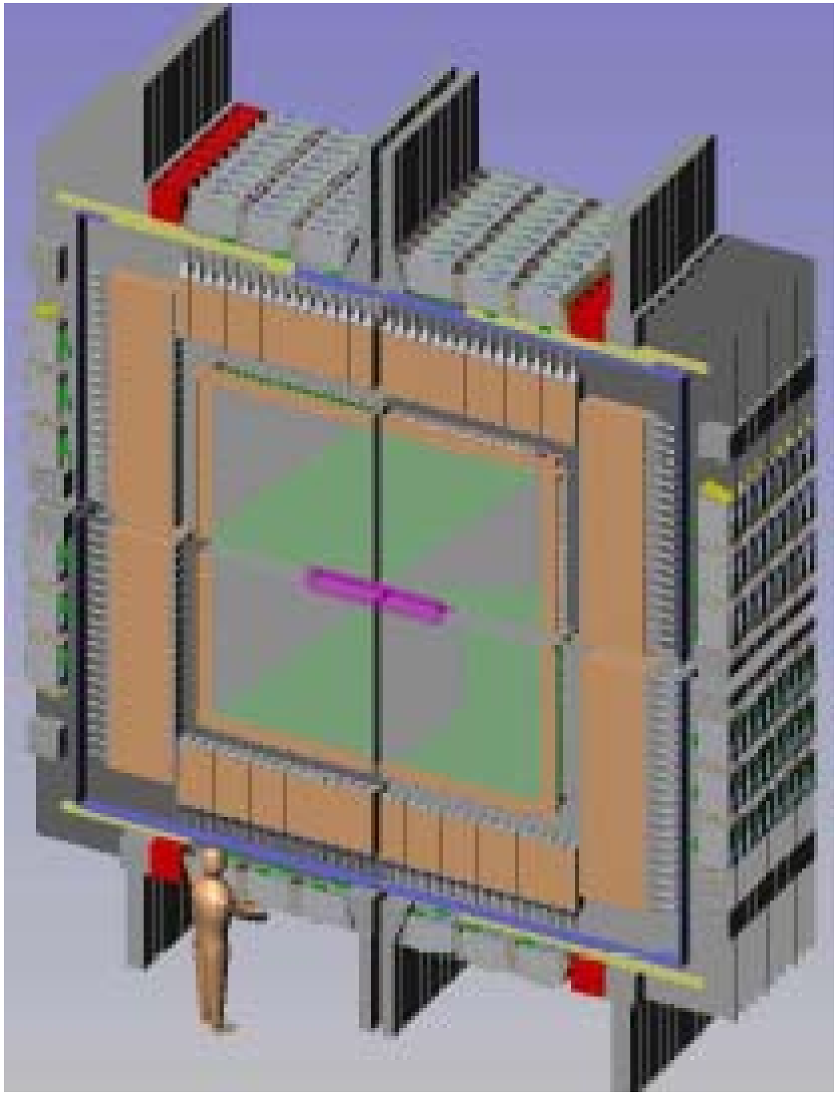
Limit based on $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ via isospin : $< 1.4 x 10^{-9}$ • $[Grossman, Nir]$

- **KTeV (FNAL): $B(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$ (90% CL)**
- **KEK E391a >10^{-9} ?? $\Rightarrow$ J-PARC LOI**
- **KOPIO (BNL): single event sensitivity <10^{-12}**
  - ***Discovery* (5σ) for $B(K_L \rightarrow \pi^0 \nu \bar{\nu}) > 5 \times 10^{-11}$ or <1.8×10^{-11}**
  - **If nothing new, ~300 SM events**
    - **Rule out BRs outside of $(1 \pm 0.17) BR_{SM}$ @ 95%CL**
    - **Bound operators, B-system can't access**

KOPIO Parameters

• μ bunch width (extinction)	200ps (10^{-3})
• Beam halo	10^{-4}
• Vacuum	10^{-7} Torr
• θ_γ resolution @ 250MeV	25 mr
• E_γ resolution	$2.7\%/\sqrt{E_\gamma(\mathrm{GeV})}$
• t_γ resolution	$90\mathrm{ps}/\sqrt{E_\gamma(\mathrm{GeV})}$
• γ veto inefficiency(outside beam)	E949 or better
• γ veto efficiency(inside beam)	>99% at 300 MeV
• n efficiency (inside beam)	<0.3% at 800 MeV
• Charged particle inefficiency	$2\bullet10^{-5}(\pi^+)$, $1.2\bullet10^{-}$

Preradiator

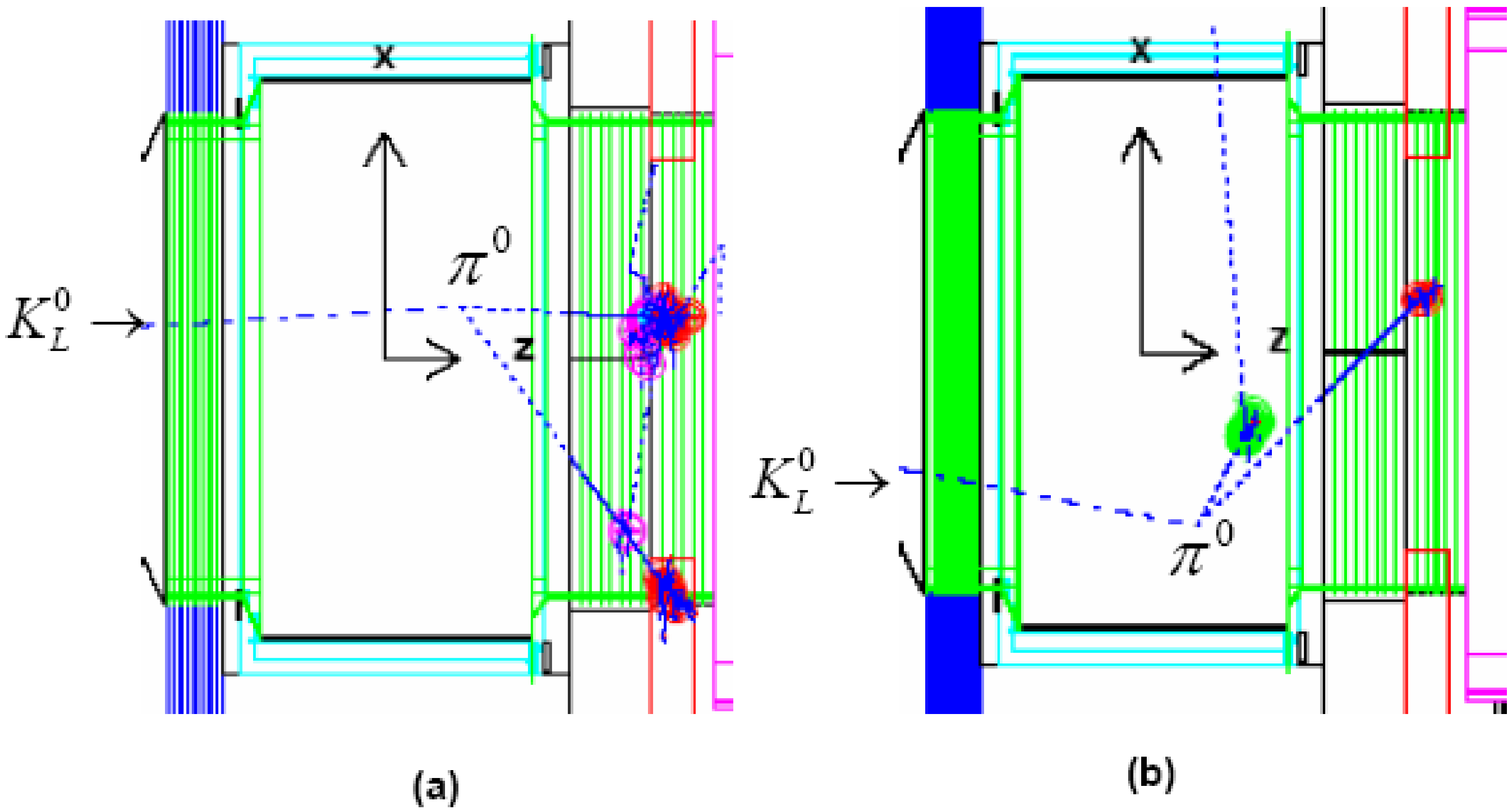


4m

64 Layers (4% X_0/layer, 2.7 X_0)
256 Chambers
288 Scintillator Plates (1200 $m^{2)}$
150,000 Channels Readout

Primary **detection mode:**
2 photons covert in preradiator

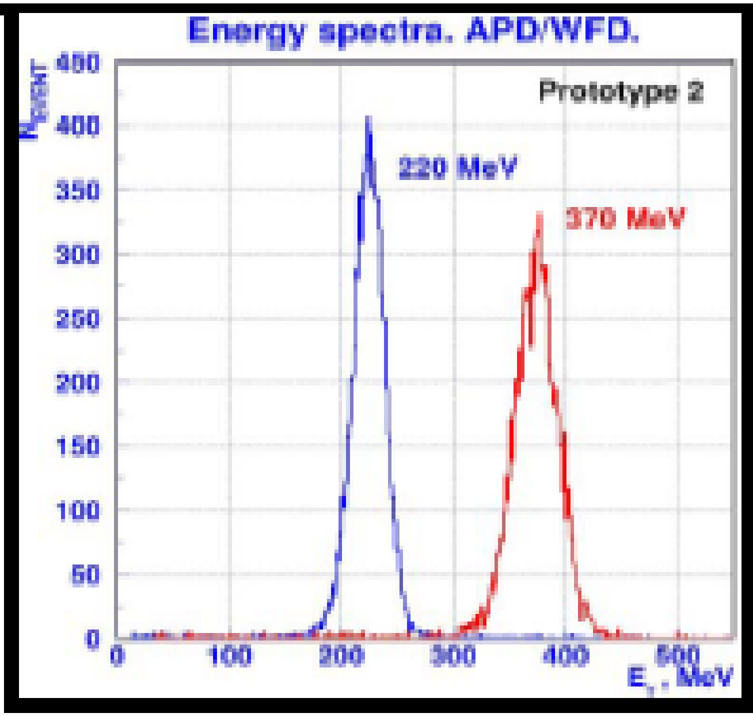
Secondary mode:
1 photon in preradiator, 1 in BV

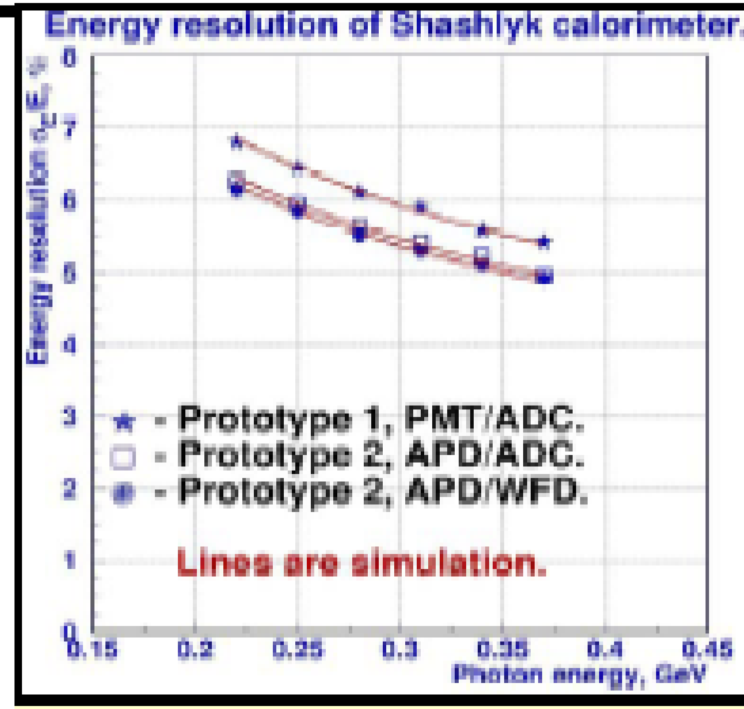


Reconstruct 1st $\gamma \rightarrow e^+e^-$ in "Preradiator",

Point to K decay vertex in vacuum

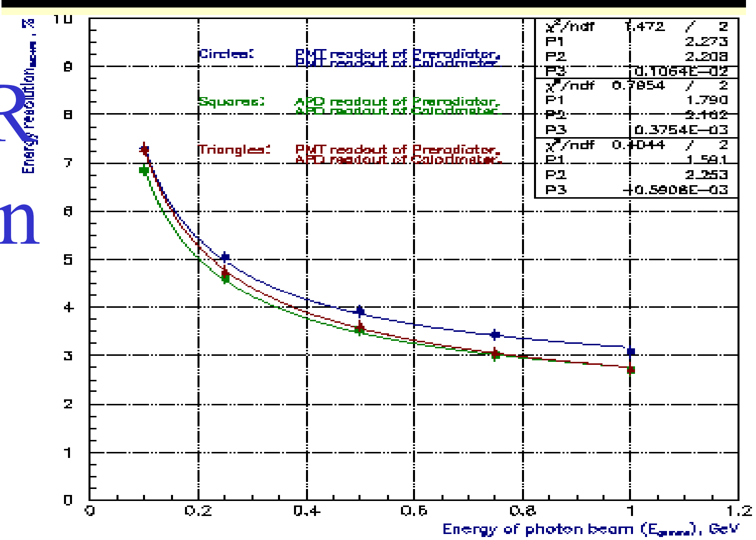
Shashlyk Beam Measurements





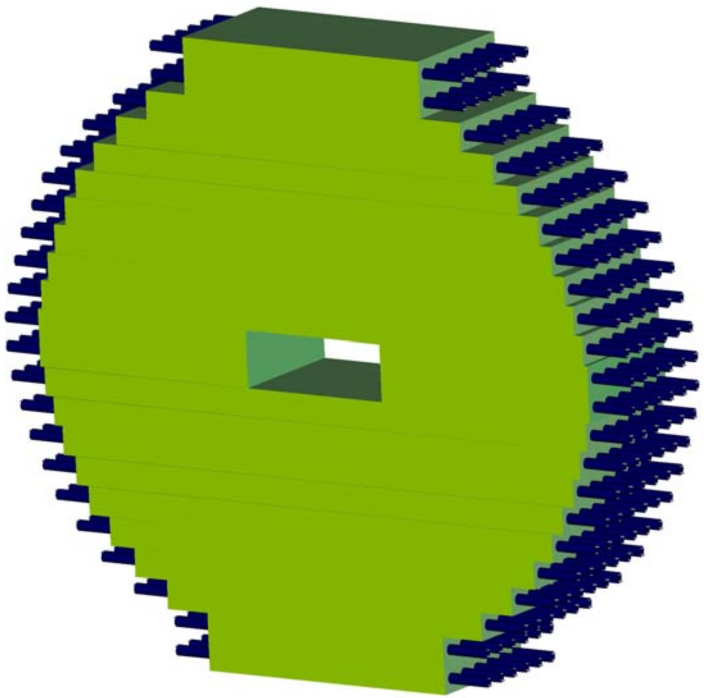
Simulation: Combined PR + CAL Energy Resolution

$$\sigma = \frac{2.7\%}{\sqrt{E(GeV)}}$$



Barrel Veto/Calorimeter

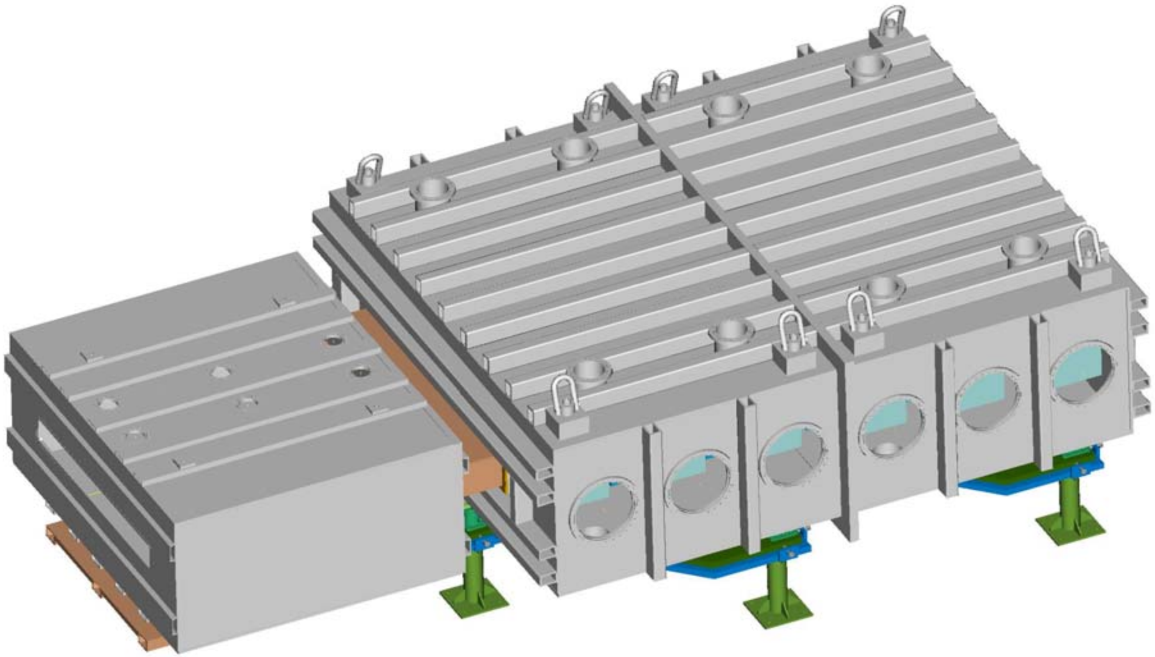
- Cylindrical array of 840 modules with 2.5m ID
- Both signal detection an[d] vetoing functions
  - 1γ in prerad + 1γ in BV/C
- Modified version of calorimeter shashlyk technology, pmt readout
  - Energy resolution calcula[ted] to be almost as good as calorimeter
  - Time resolution should b[e] comparable
- B V/C lined with thin, high-efficiency, charged particle veto scintillators



US end of barrel sealed by wall of plate shower-counter vetoes

D4 & downstream vetoes

- Charged & γ vetoes in D4 sweeping magnet
  - Field sweeps vertically
- DS vetoes detect γ's emerging from the beam
- Lead/scintillator plate sandwich counters
- Hermeticity completed by catcher veto at the back



Primary Backgrounds

Worst backgrounds are from K_L decay

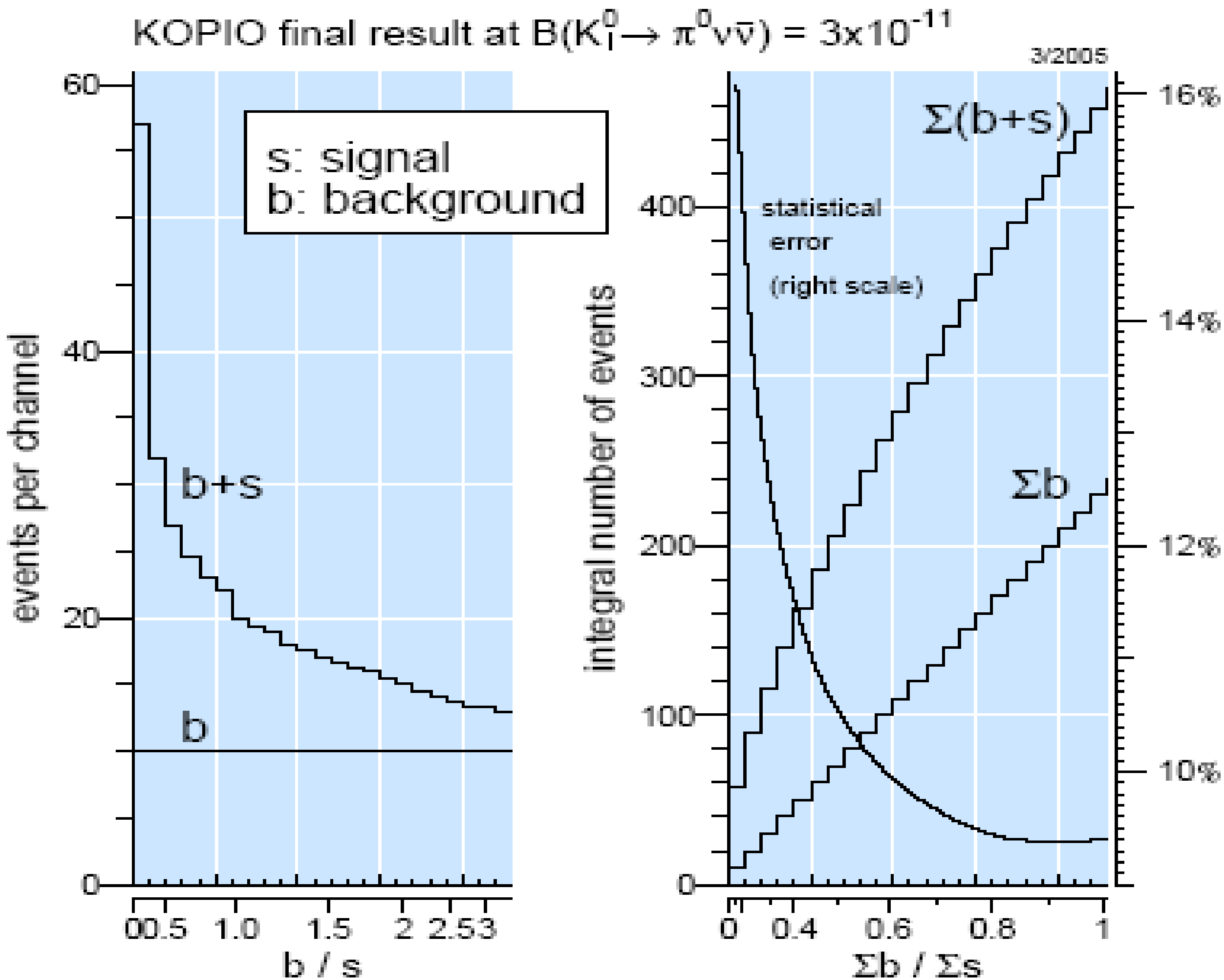
Background suppression factor needed: 10^{10}

Mode	Branching Ratio	Rejections
$K_L^0 \rightarrow \pi^0\pi^0$	$0.93\ x\ 10^{-3}$	K * PV^2
$K_L^0 \rightarrow \pi^- e^+ \nu\, \gamma$	$0.36\ x\ 10^{-2}$	K * C^2 * PV
$K_L^0 \rightarrow \pi^+\pi^-\pi^0$	0.1255	K * C^2
$K_L^0 \rightarrow \pi^0\pi^0\pi^0$	0.2105	K * PV^4
Others		

Simulation Tools

- GEANT3
  - FLUKA, GCALOR, GHEISHA hadronic packages
- GEANT4
- FLUKA
- MCNPX
- MARS
- KOPTICs
  - custom optics simulator
- FastMC
  - uses input from detailed simulators + input from experiments
- Critical parameters directly measured
  - Either in prototype tests or experiments

Alternative Display of Results



KOPIO Operations Plan

- **2010 Test Run – partial detector**
- **2011 Engineering Run**

  "Discovery phase": Sensitivity goal:~10^{-10}
- **2012-16 Data Acquisition**

Branching Ratio Measurement Precision

- Precision at $B(K_L \rightarrow \pi^0 \upsilon\upsilon) = 3\times10^{-11}$
  Using probability likelihood method employing all observed events (approximately 300)
  $\pm 10\%$
- (Statistical) Precision on Im λ_t: $\pm 5\%$